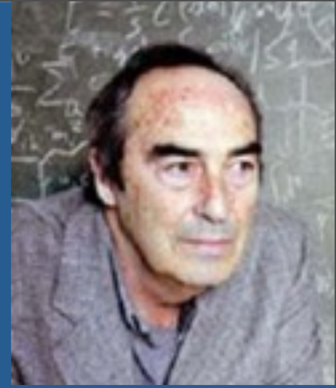
Paco Yndurain Colloquium
May 4, 2011



# *Neutrino oscillations*
## *Discovery, status and future directions*

Takaaki Kajita
ICRR, Univ. of Tokyo

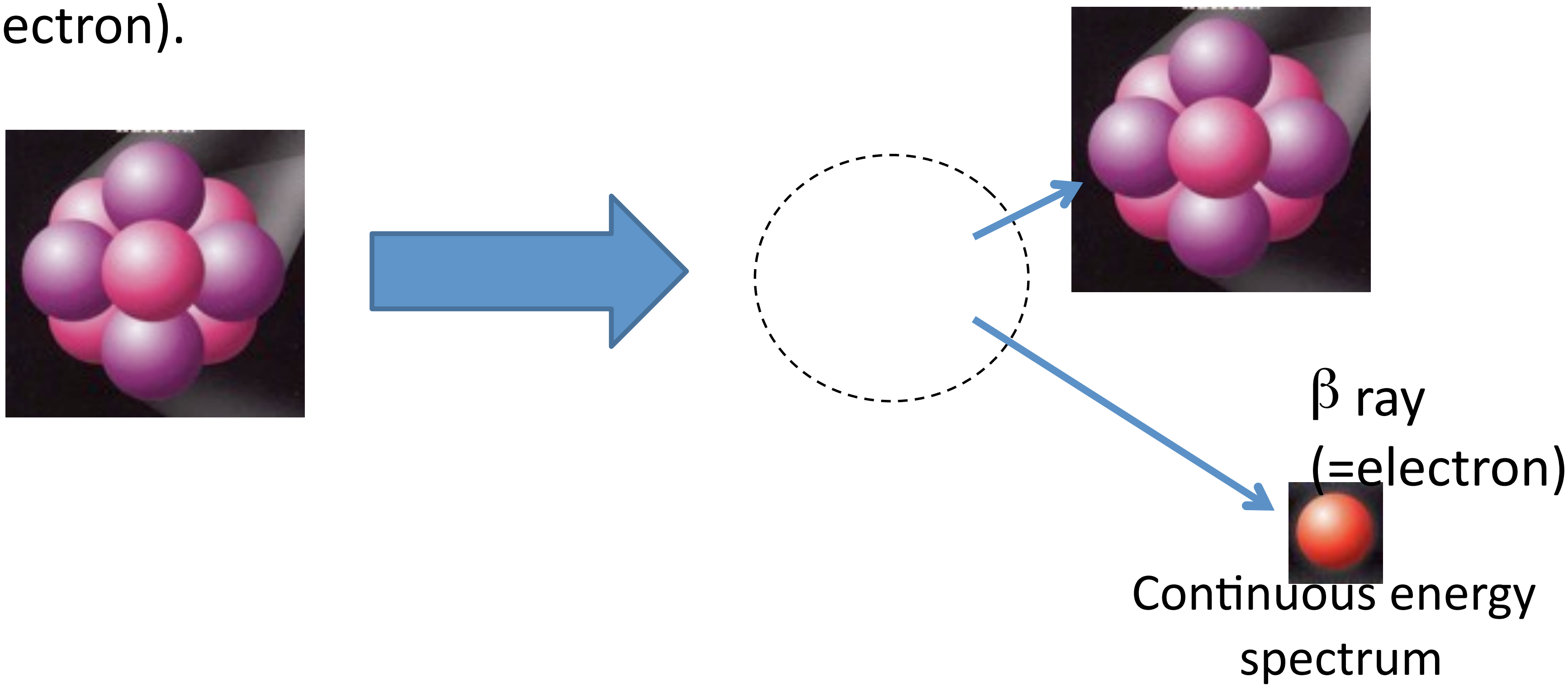
# *outline*

- Introduction
- Neutrino masses and neutrino oscillations
- Discovery of neutrino oscillations: Part I
- Discovery of neutrino oscillations: Part II
- Future prospects
- Summary

# *Introduction*

# *Mystery of β decay*

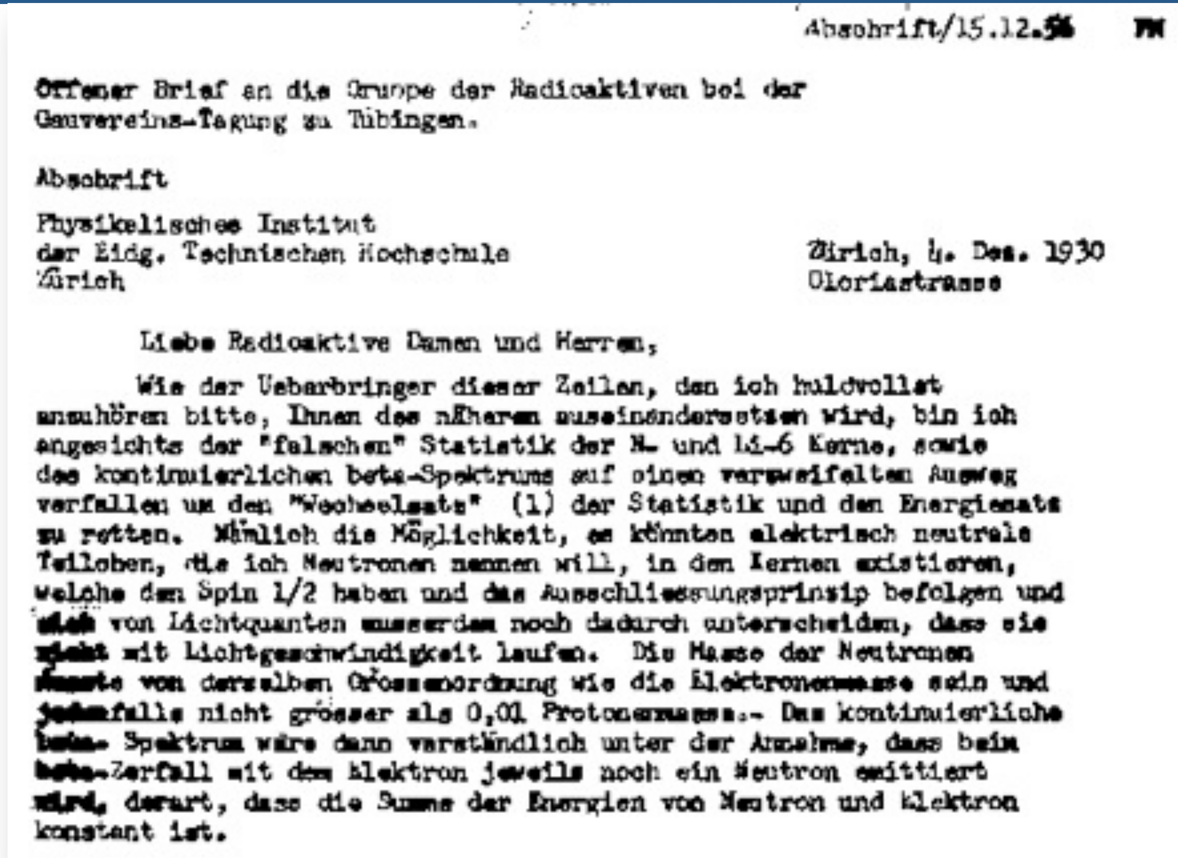
In early 20$^{th}$ century, people observed that a certain kind of nucleus spontaneously change to a different nucleus by emitting β ray (electron).




This phenomena had serious mysteries, since it apparently did not to conserve energy, momentum and spin.

# Introduction of neutrino

W. Pauli



Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

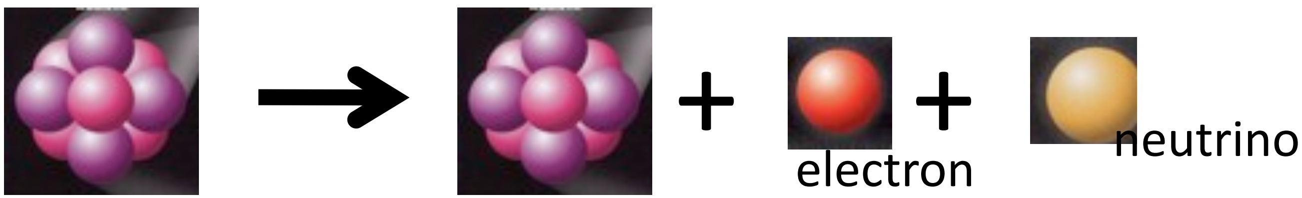
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

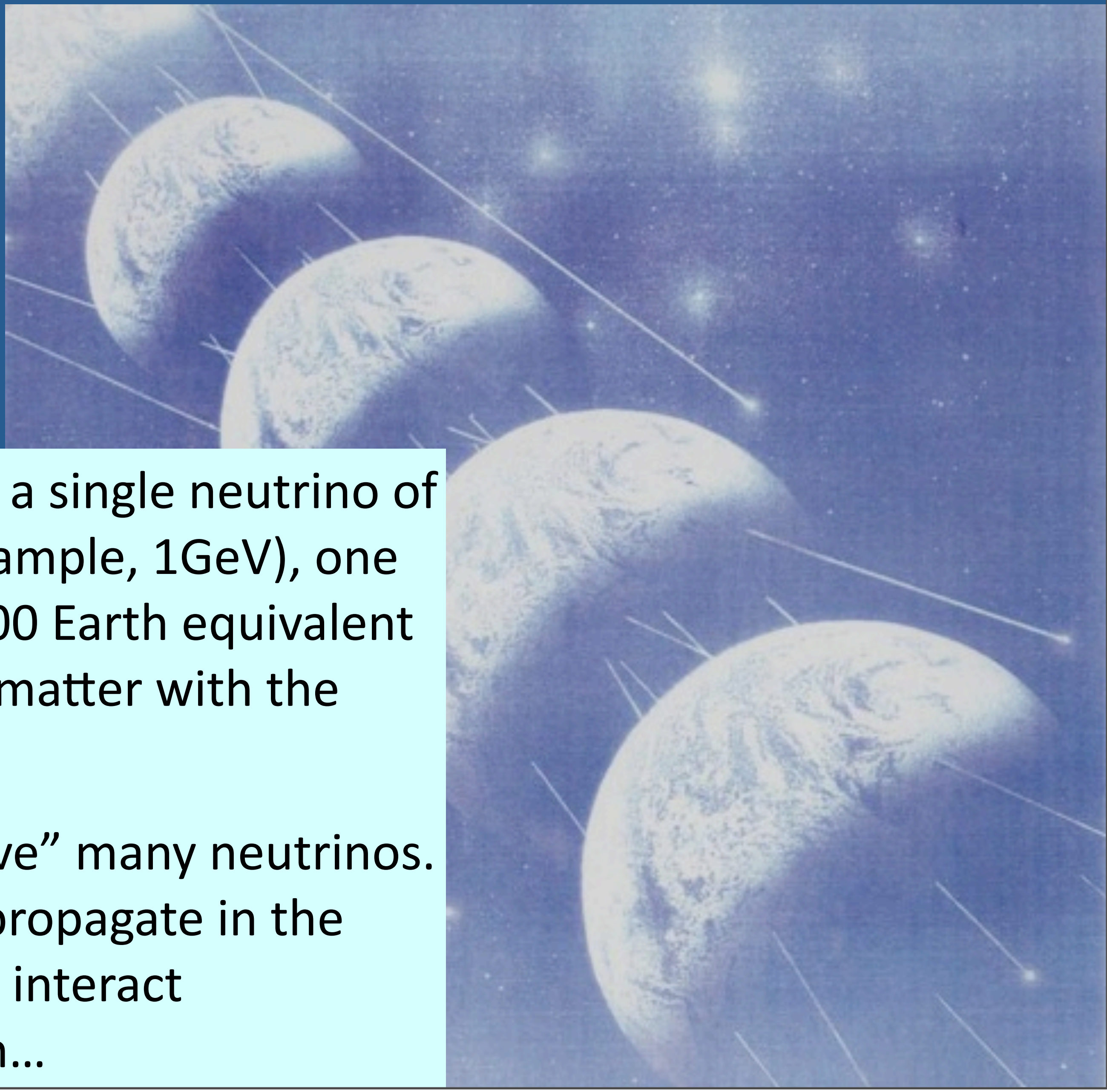
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

W. Pauli, in his letter to “Radioactive Ladies and Gentleman” at Tubingen, in Dec. 1930, pointed out that there could exist neutral particles which have spin 1/2 (neutrino).



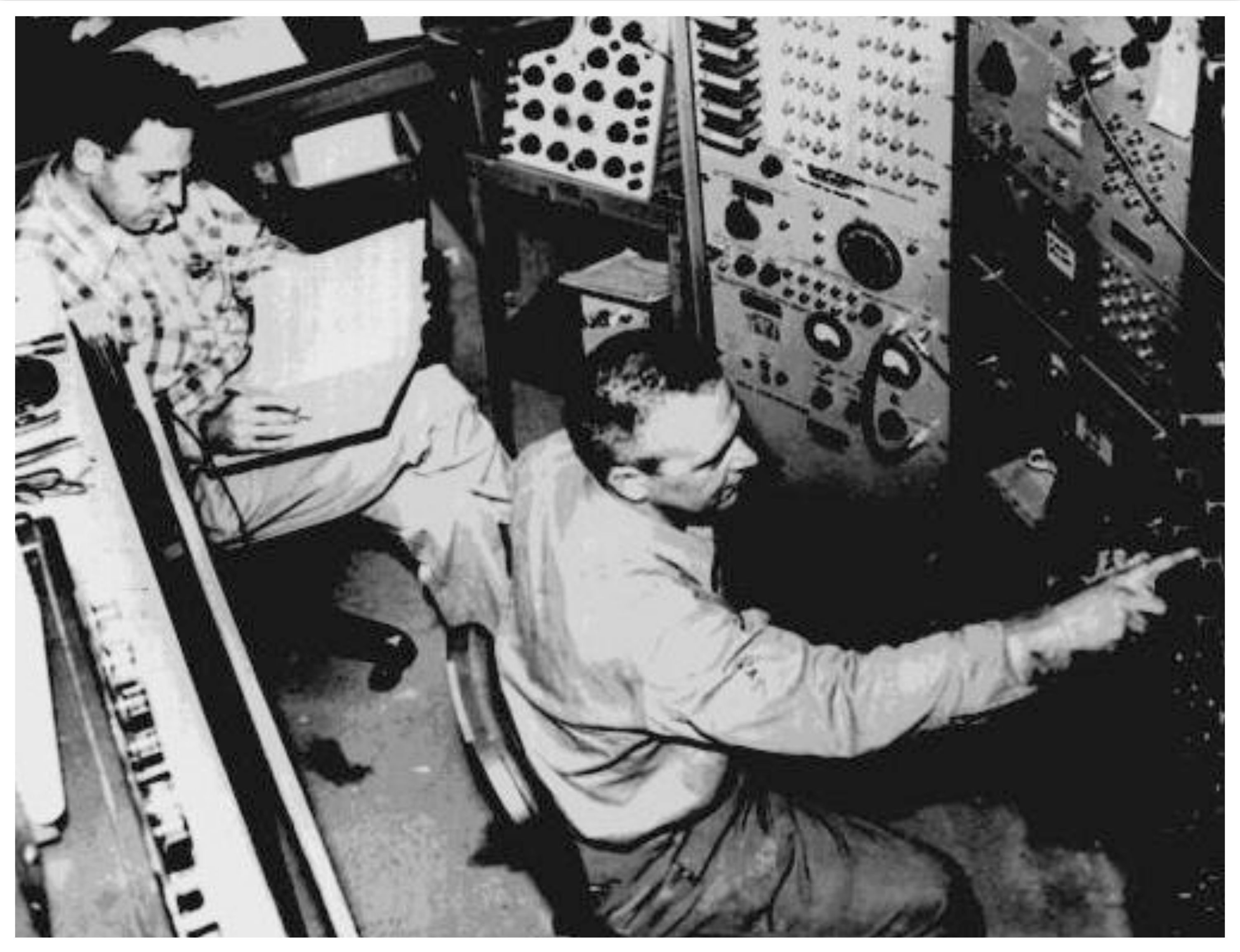
# *Neutrinos are difficult to observe*



If one wants to observe a single neutrino of a certain energy (for example, 1GeV), one typically needs 1,000,000 Earth equivalent matter (i.e., $10^{10}$ km of matter with the typical earth density).

➔ One has to "observe" many neutrinos. If 1,000,000 neutrinos propagate in the Earth, one of them may interact somewhere in the Earth…

# *Discovery of electron-(anti-)neutrino (1950's)*

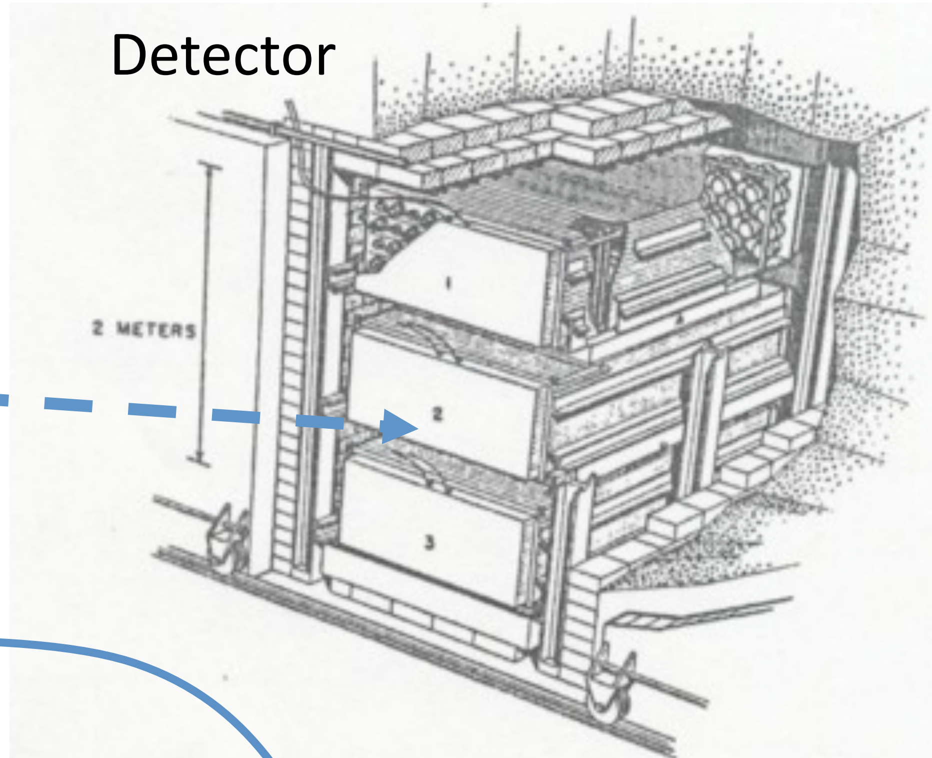


F. Reines (right, Nobel Prize, 1995) and C. Cowan Jr.

# Discovery of electron-(anti-)neutrino (1950')

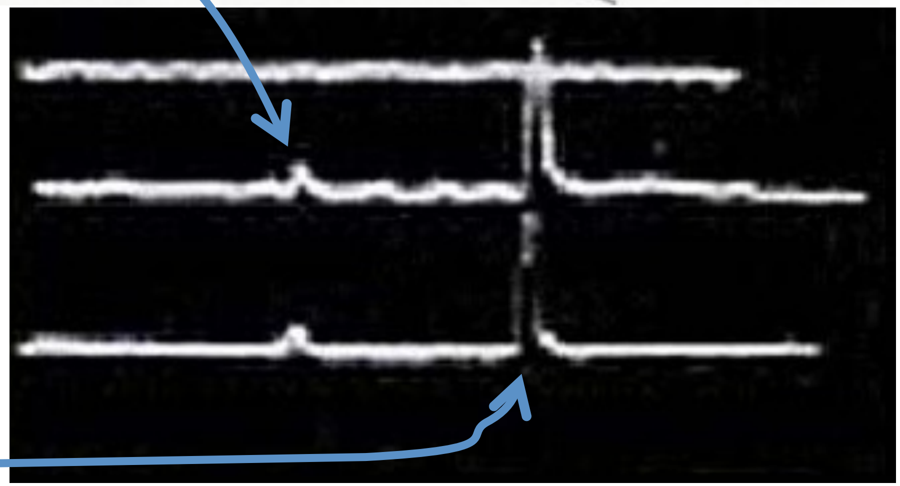
Savanna River reactor

$\bar{\nu}_e$




$\bar{\nu}_e\, p$ ® $e^+ n$

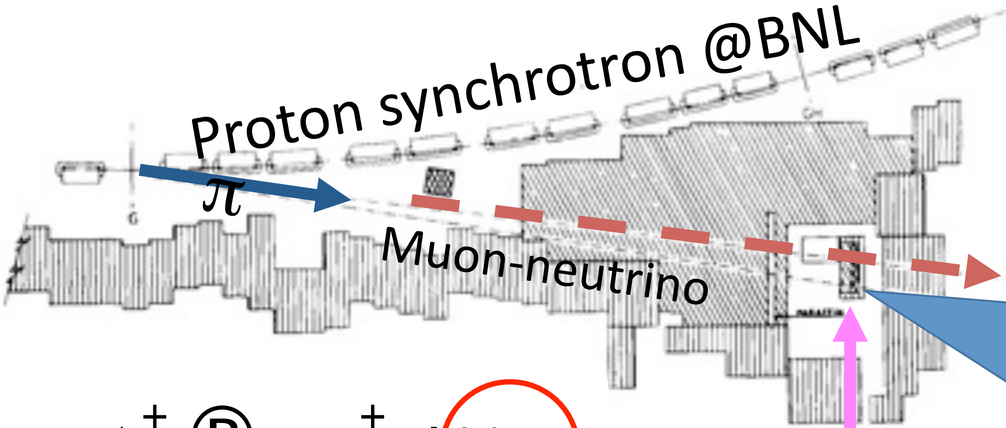
followed by neutron capture by Gd, which results in gamma ray emission.

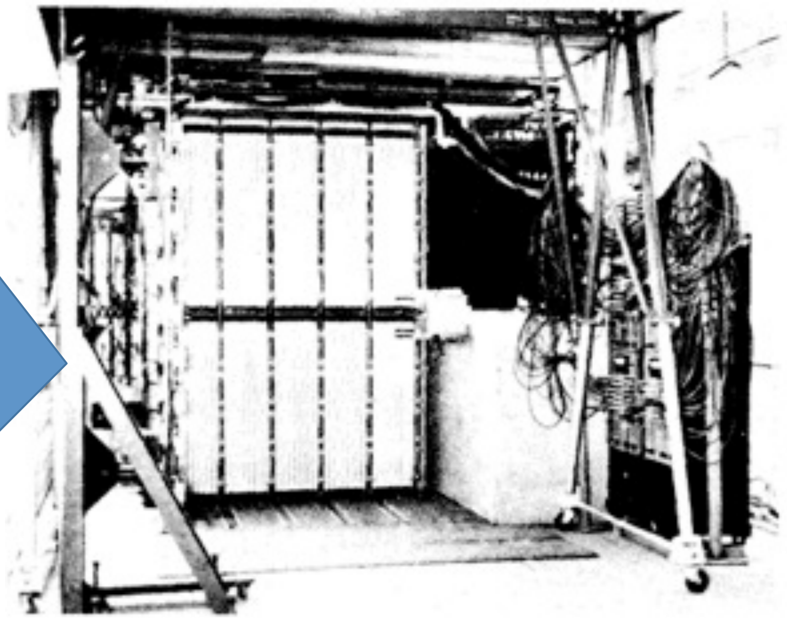


# *Discovery of muon-neutrino (1962)*

From the left to right: J.Steinberger, M.Schwartz and L.Lederman (Nobel Prize, 1988)

# Discovery of muon-neutrino (1962)



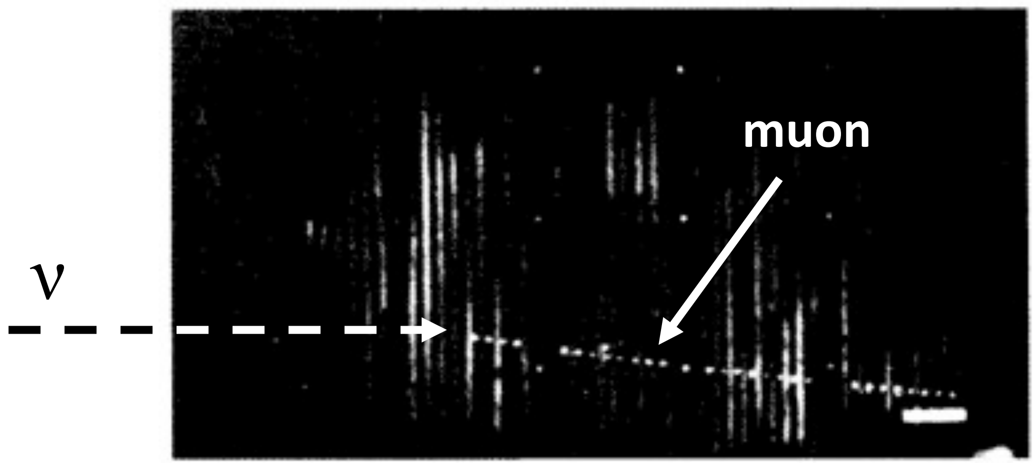
$\pi^{+}$ ® $\mu^{+} + \nu_{\mu}$

Neutrino production

Neutrino detector

$\nu_{\mu} + n$ ® $\mu^{-} + p$

Neutrino detection




One of the observed events

# Matter elementary particles

# *Neutrino masses and neutrino oscillations*

# *Neutrinos are special*

- There used to be no evidence for mass. Therefore, it has been assumed that neutrinos are massless in the Standard Model of particle physics.
- They have no electric charge.
- They only “feel” weak force.
- …

# Neutrinos are special

- There used to be no evidence for mass. Therefore, it has been assumed that neutrinos are massless in the Standard Model of particle physics.
- They have no electric charge.
- They only “feel” weak force.
- …

However,

Maki

Nakagawa

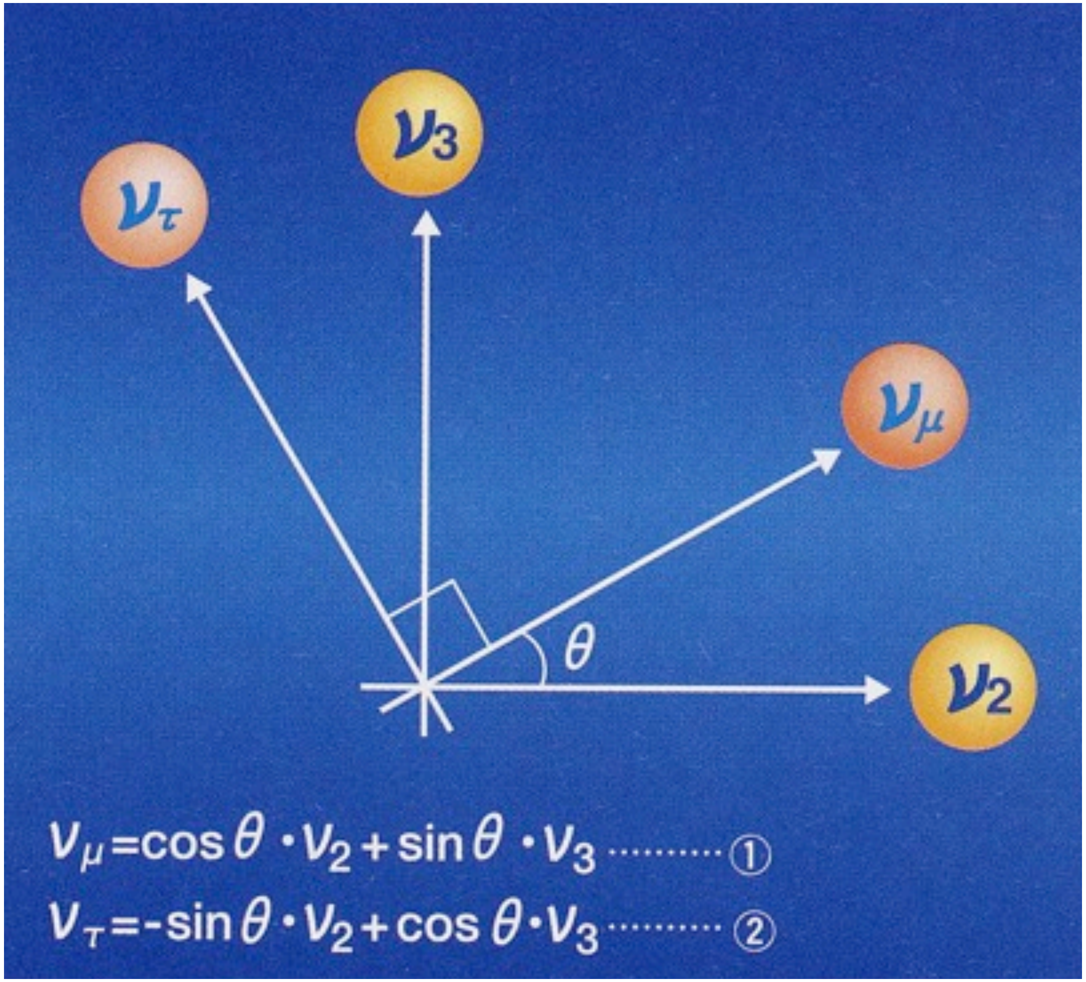
Sakata

Pontecorvo

What will happen if neutrinos have masses…. ?

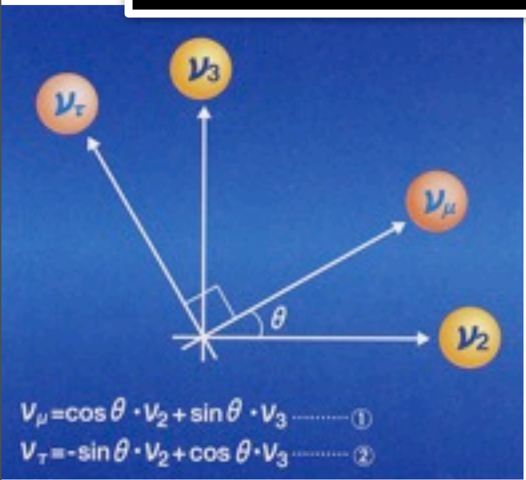
# Neutrino masses

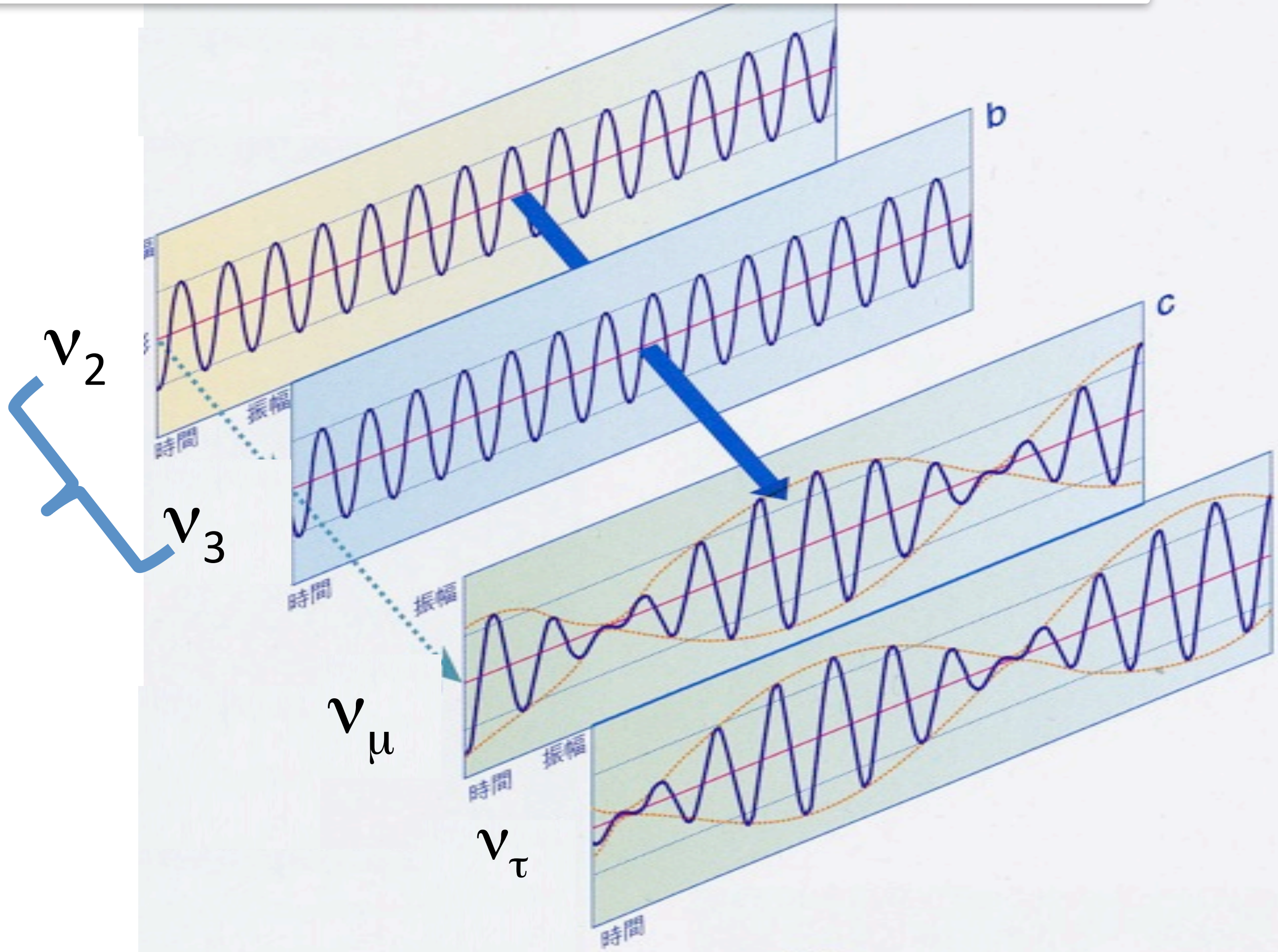
Neutrinos can be massive.
However, according to Quantum mechanics, it is generally not required that a certain type of neutrino (for example, $\nu_\mu$) to have a unique mass value.
Instead;



# Neutrino masses and neutrino oscillations

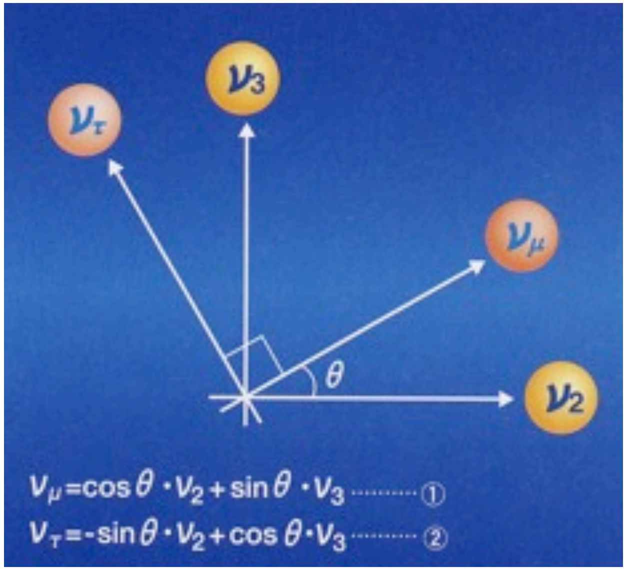
Let us consider propagation of a neutrino (for example, initially $\nu_\mu$).

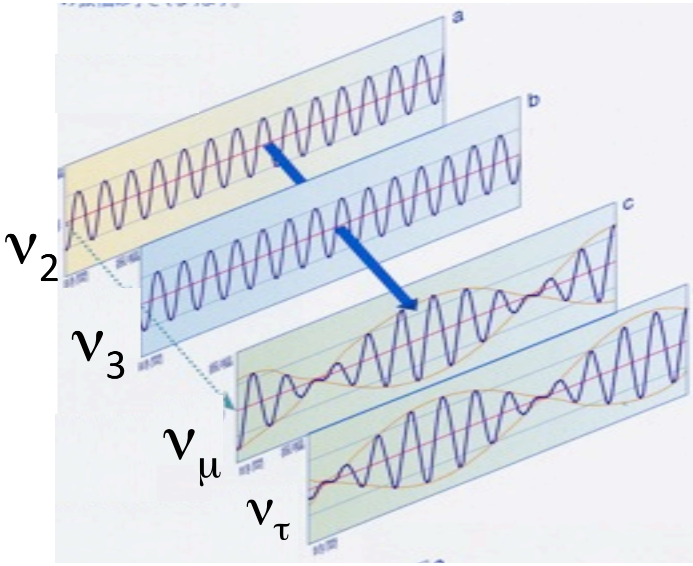



If neutrinos have masses, neutrinos change their type while propagating in the vacuum (or in a medium).

# *Neutrino masses and neutrino oscillations*



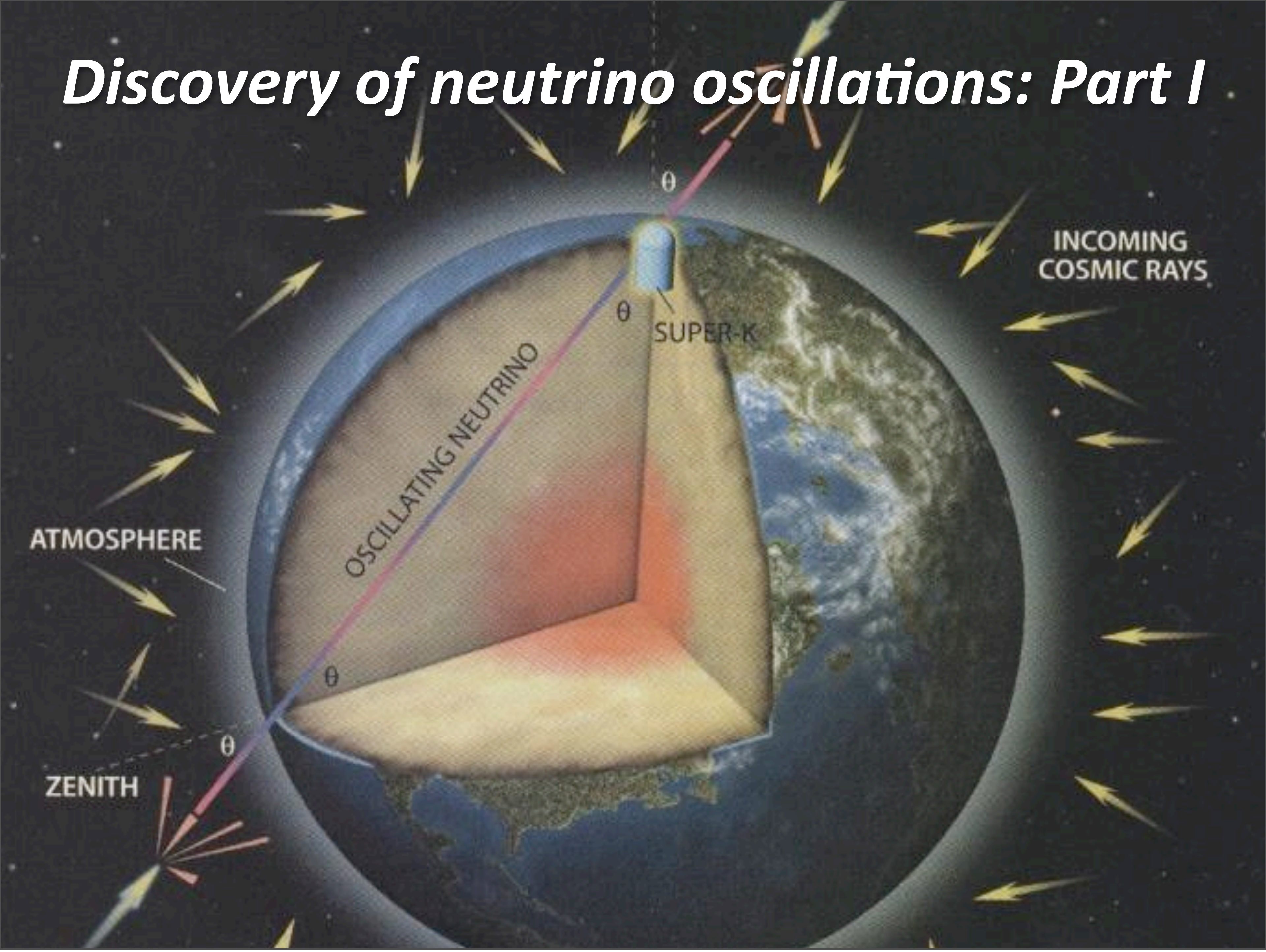

$$P(\nu_\mu \circledR \nu_\mu) = 1 - \sin^2 2\theta \times \sin^2\left(\frac{1.27\Delta m^2 \times L(km)}{E_\nu\,(GeV)}\right)$$

Used in most part of this talk.

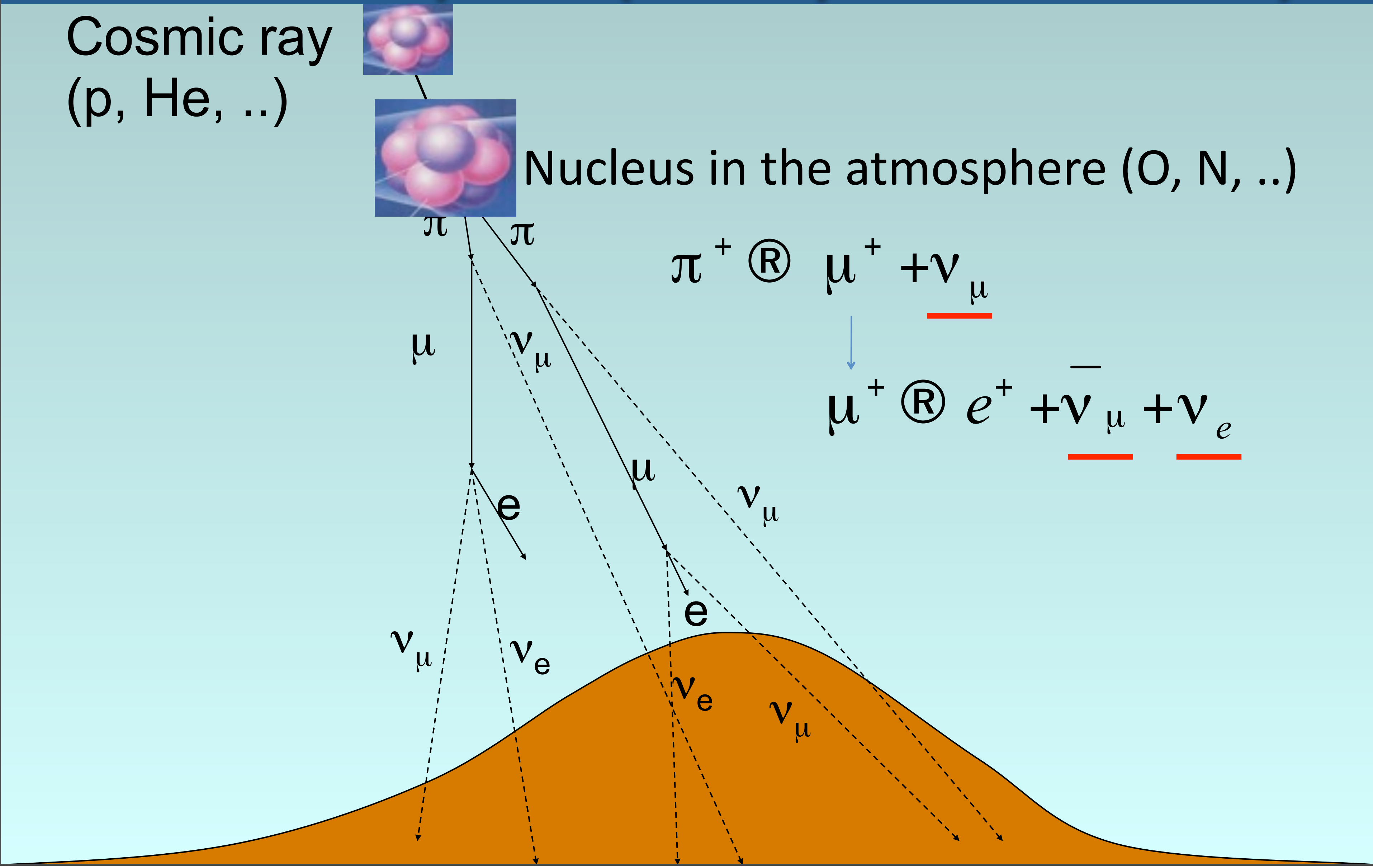
$$where\ (\Delta m^2 = \left|m_{\nu_3}{}^2 - m_{\nu_2}{}^2\right| eV^2).$$

$$P(\nu_\mu \circledR \nu_\tau) + P(\nu_\mu \circledR \nu_\mu) = 1$$

# *Discovery of neutrino oscillations: Part I*



# Neutrino production by cosmic ray interactions in the atmosphere (atmospheric neutrinos)

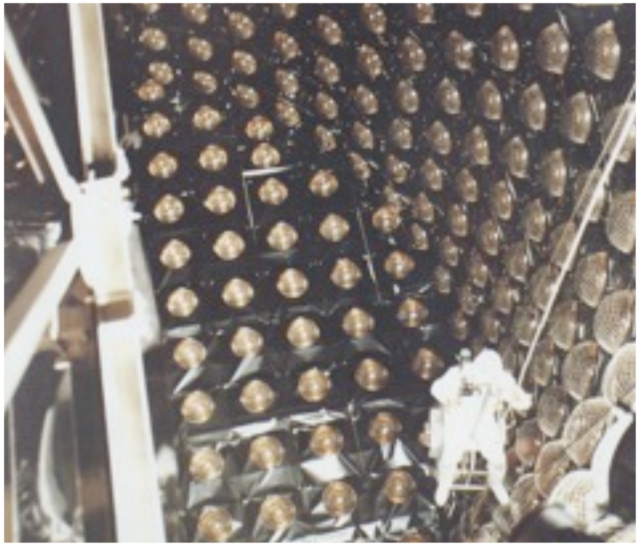



$\pi^{+}$ ® $\mu^{+} + \nu_{\mu}$

$\mu^{+}$ ® $e^{+} + \bar{\nu}_{\mu} + \nu_{e}$

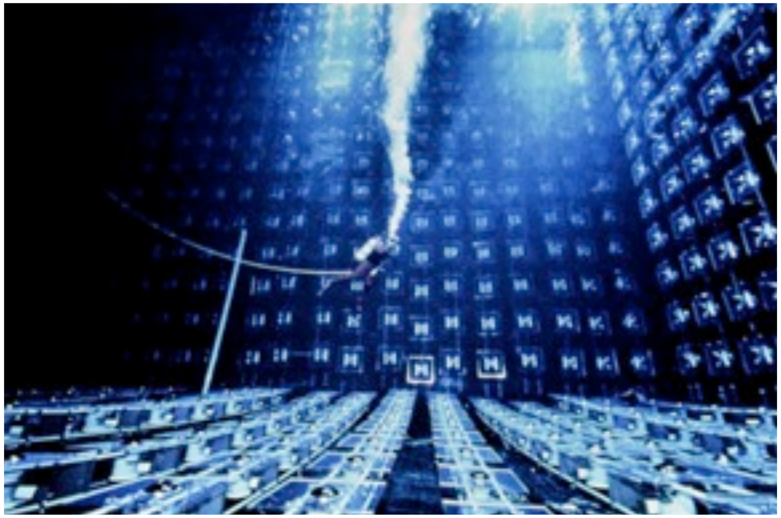
# *Proton decay experiments (1980's)*

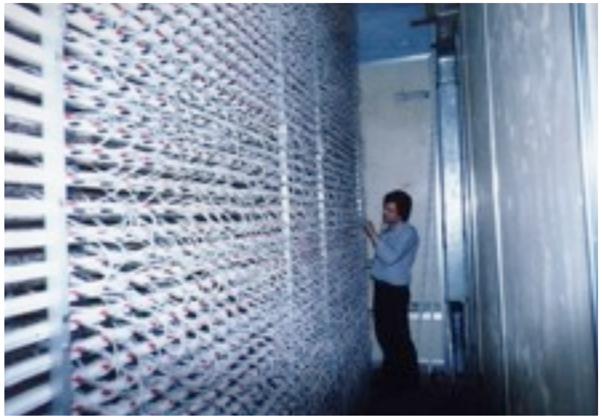
Grand Unified Theories (in the 1970's) → $\tau_p = 10^{30\pm2}$ years



Kamiokande
(1000ton)

IMB
(3300ton)

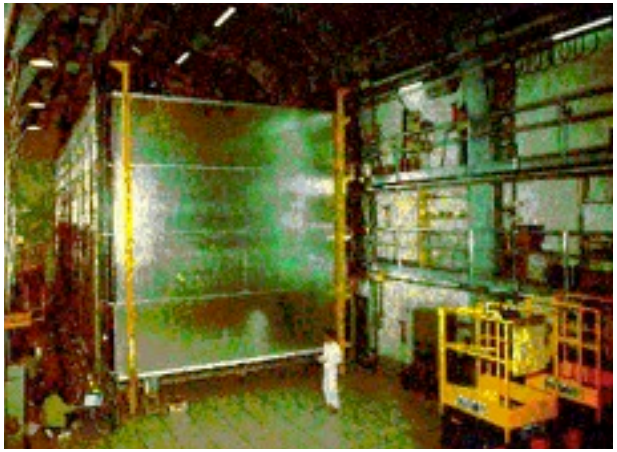




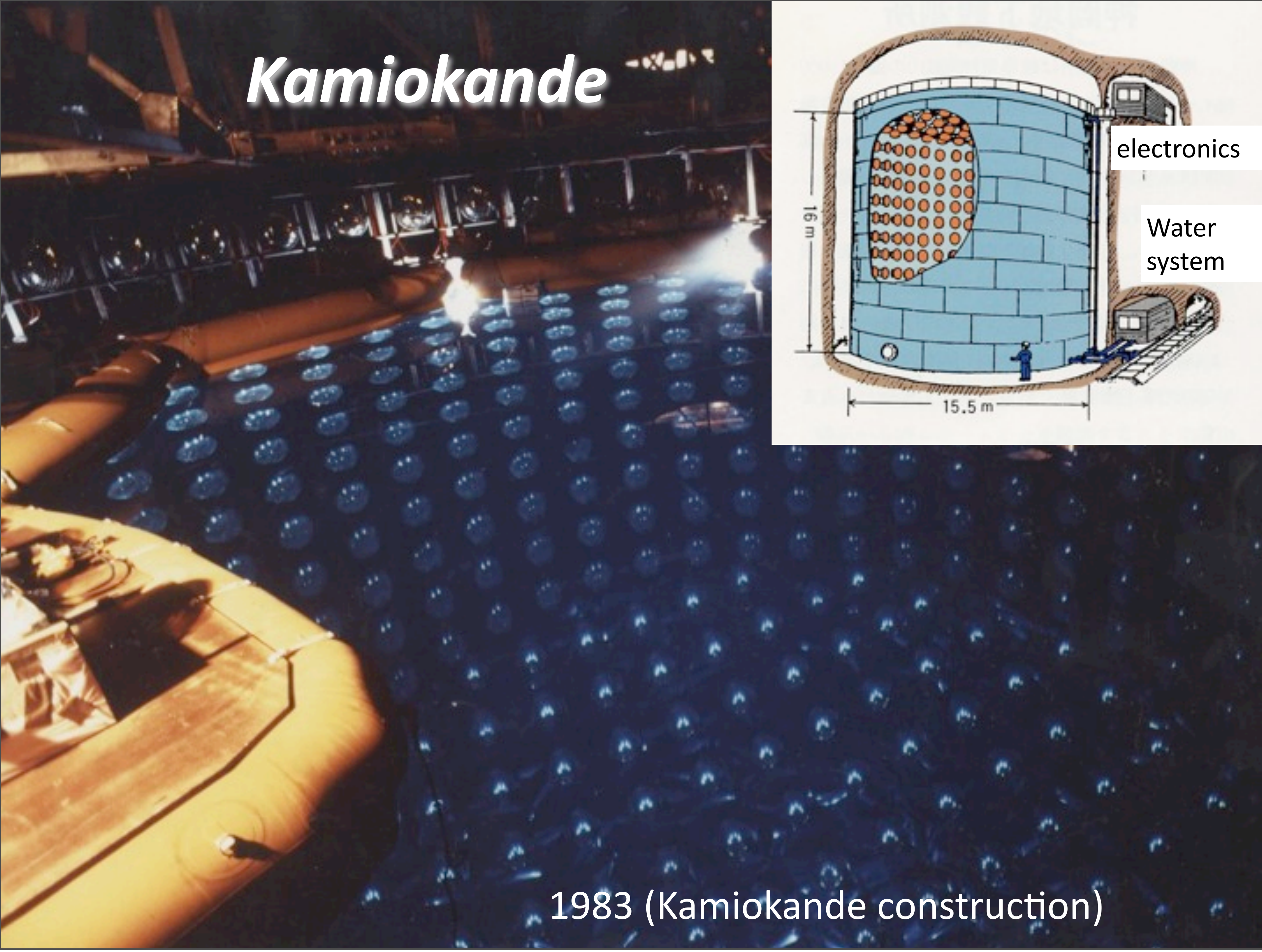
NUSEX
(130ton)

Frejus
(700ton)

These experiments observed many contained atmospheric neutrino events (background for proton decay).

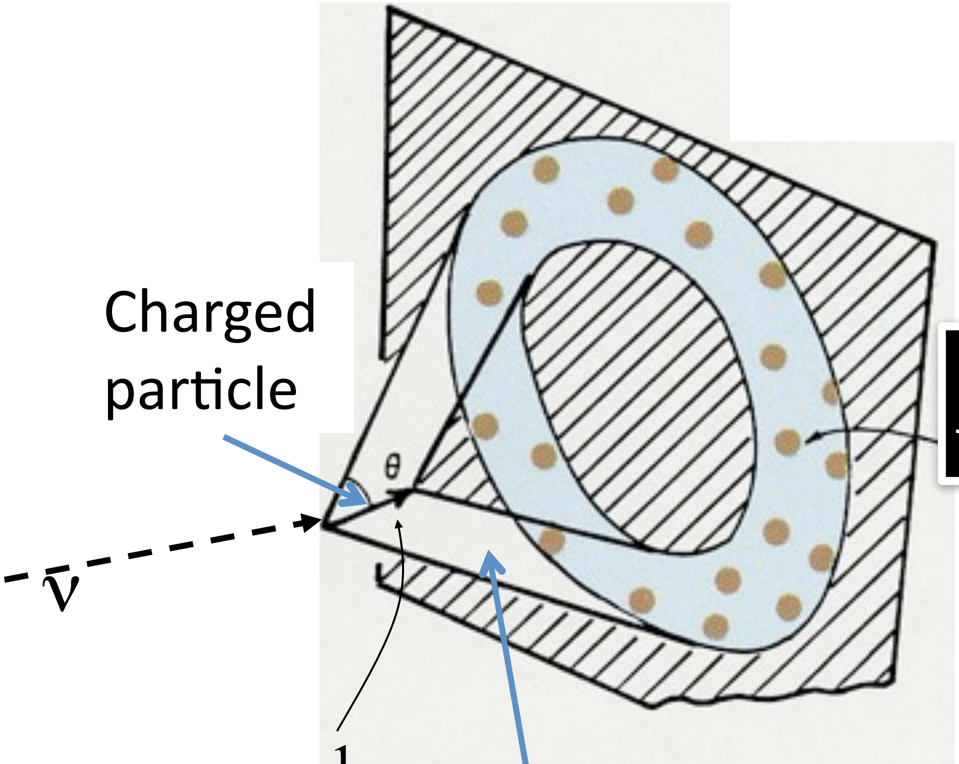


# Kamiokande




1983 (Kamiokande construction)

# Detecting Cherenkov photons




$$\cos\theta = \frac{1}{n\beta}$$

*n* (refractive index)=1.34 in water

➔ θ=42deg. for β=1

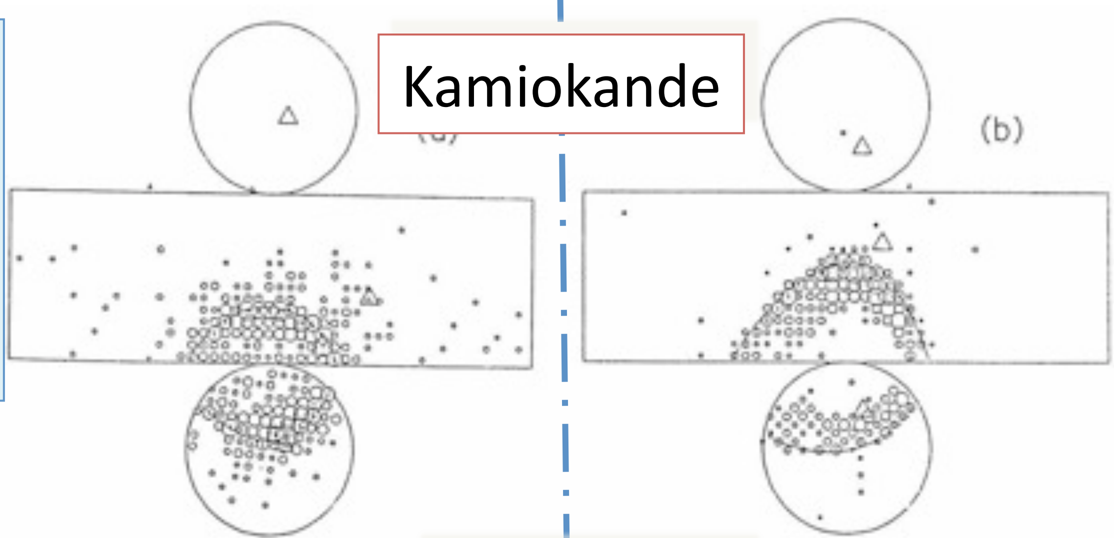

M. Koshiba (2002 Nobel Prize)

# Cherenkov rings by electrons and muons

electron-like events

($\nu_e$ N→ **e** N')

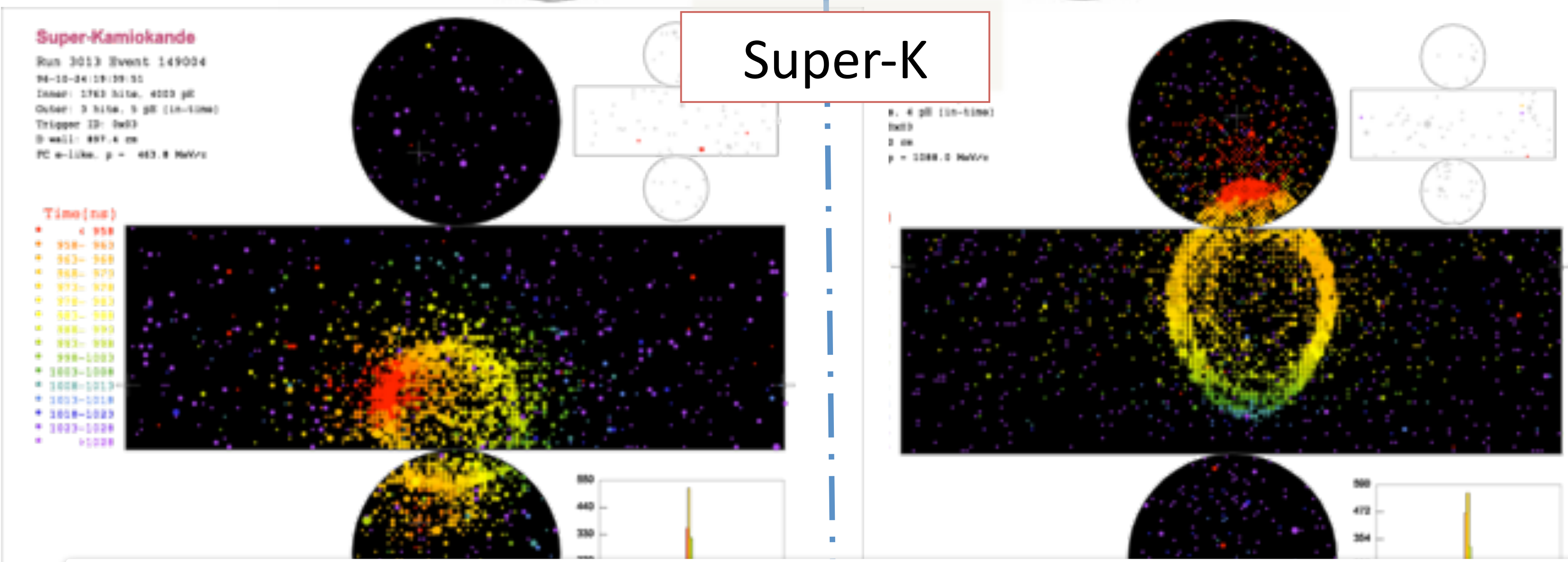
Kamiokande




muon-like events

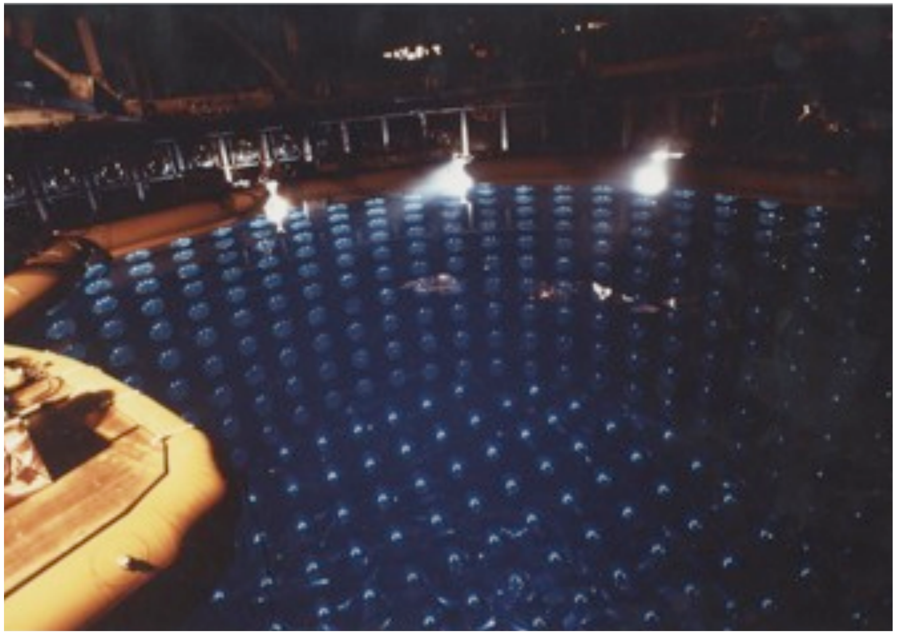
($\nu_\mu$ N→ $\mu$ N')

Super-K




Particle Identification; ε=99%@Super-K (98% @Kamiokande)

# First result on the μ/e ratio (1988)



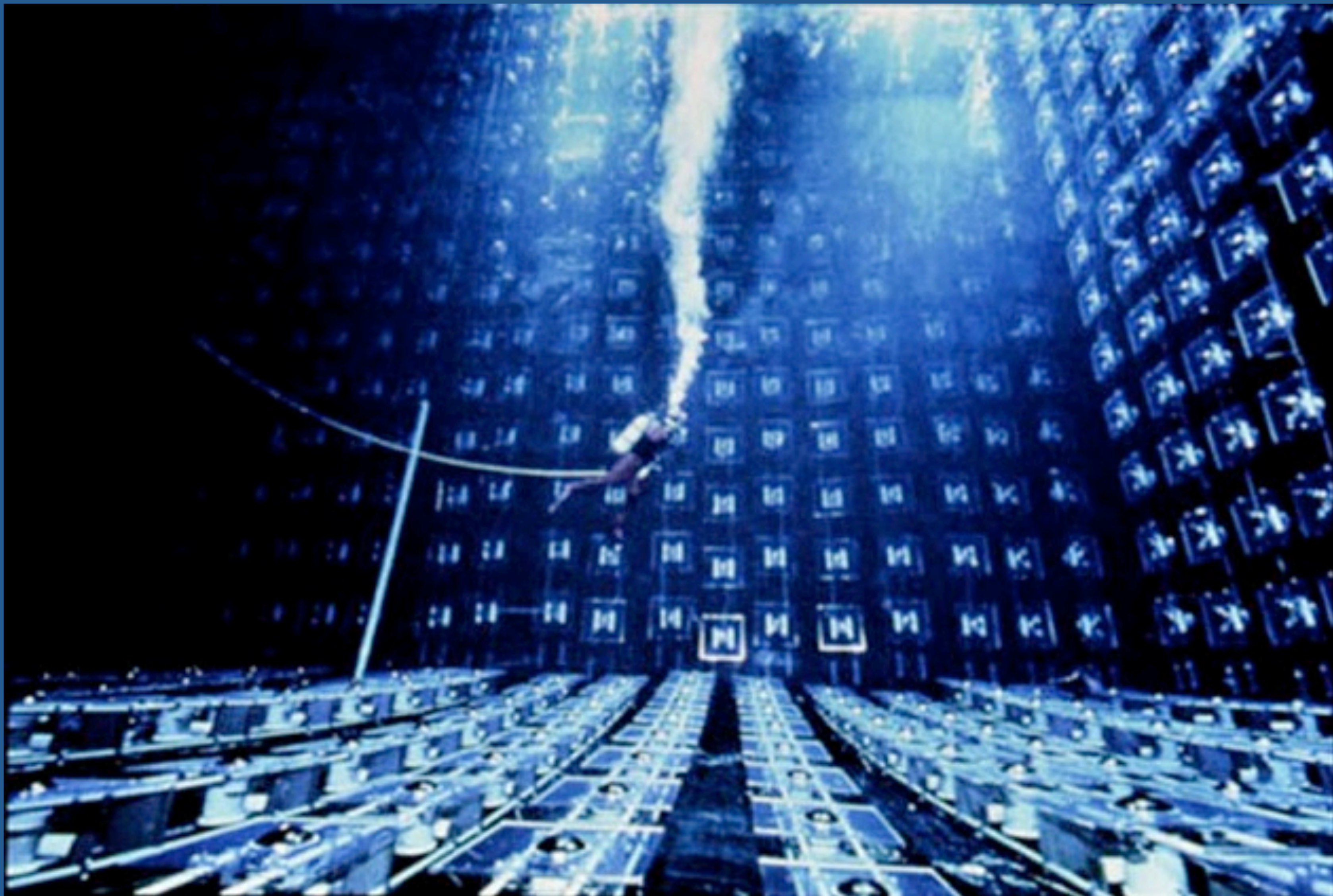
Kamiokande

| | Data | MC prediction |
|---|---|---|
| e-like (∼CC $\nu_e$) | 93 | 88.5 |
| $\mu$-like (∼ CC $\nu$) | 85 | 144.0 |

"We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccoundted-for physics such as neutrino oscillations might explain the data."

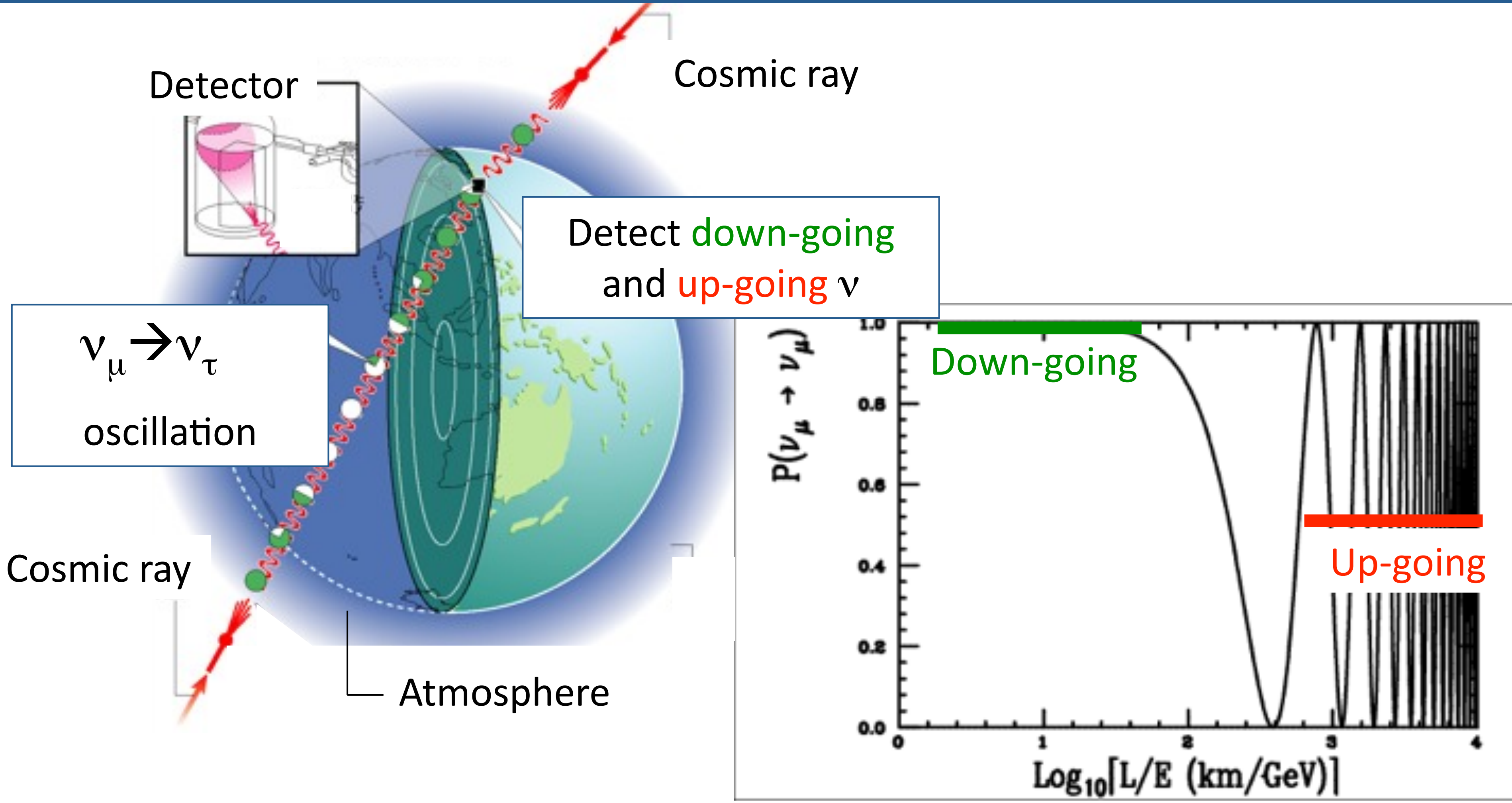
Kamiokande collab., Phys.Lett.B 205 (1988) 416.

# *First supporting result on small μ/e*

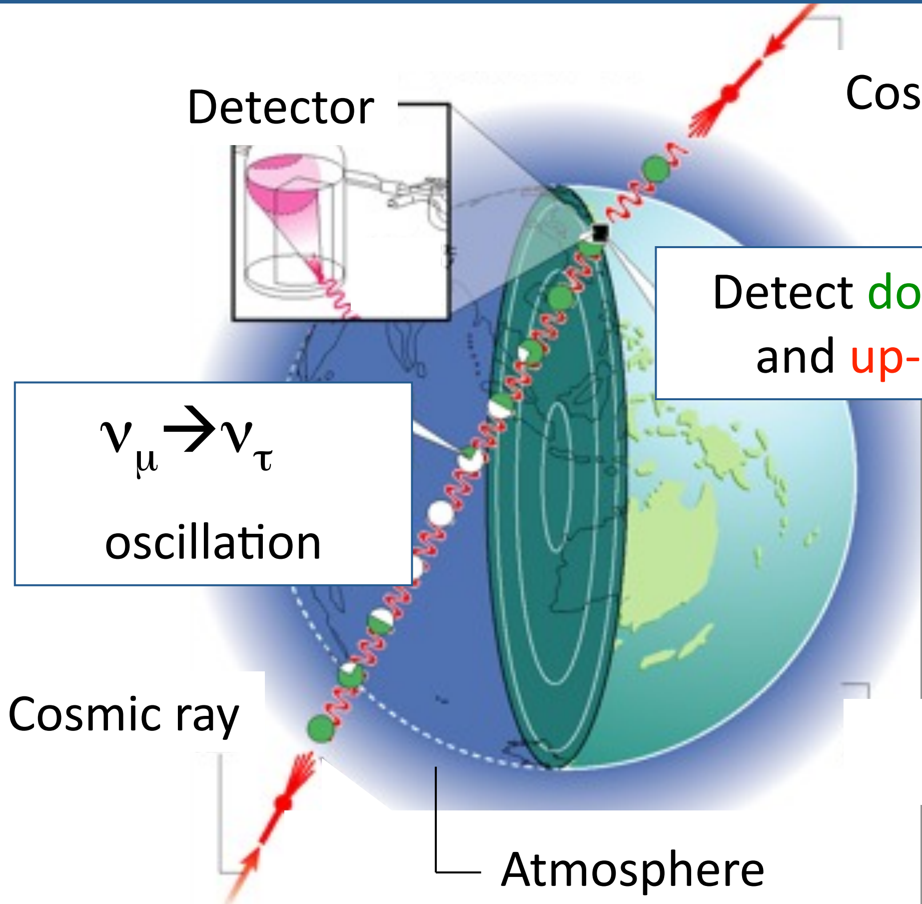


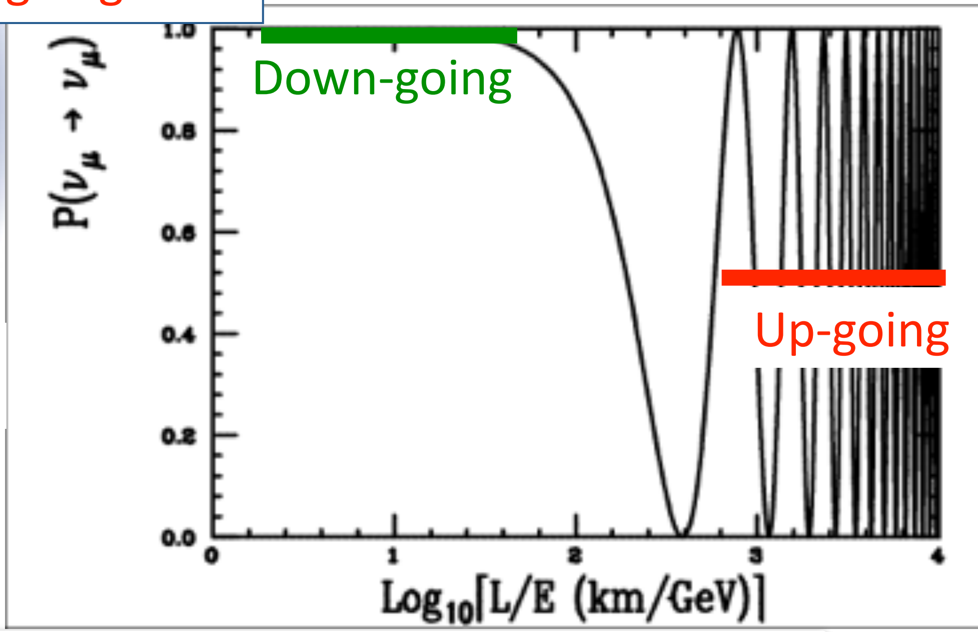
IMB experiment also reported smaller (μ/e) in 1991 and 1992.

# What will happen if the moun deficit is due to neutrino oscillations



# What will happen if the moun deficit is due to neutrino oscillations



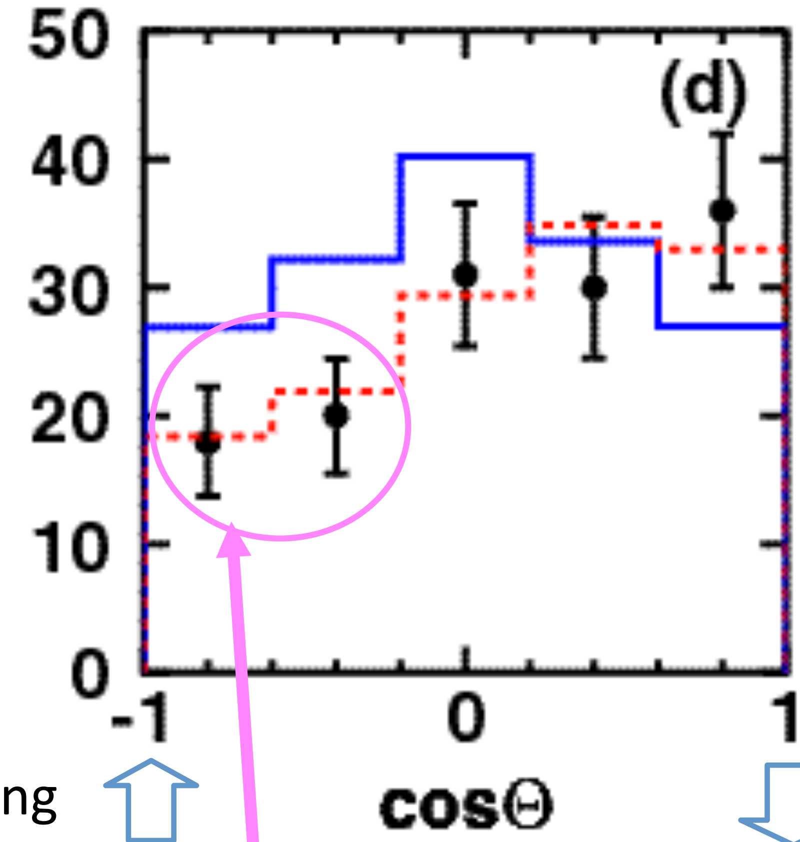

One should observe a deficit of upward going $\nu_\mu$'s (=muons) !

(A demonstration that quantum mechanics works even at the scale of the Earth!)

# Zenith angle distribution (multi-GeV)

multi-GeV
μ-like
events

Kamiokande PLB 335, 237 (1994)




No oscillation

$\nu_\mu \rightarrow \nu_\tau$ (best fit)

Up-going

Down-going

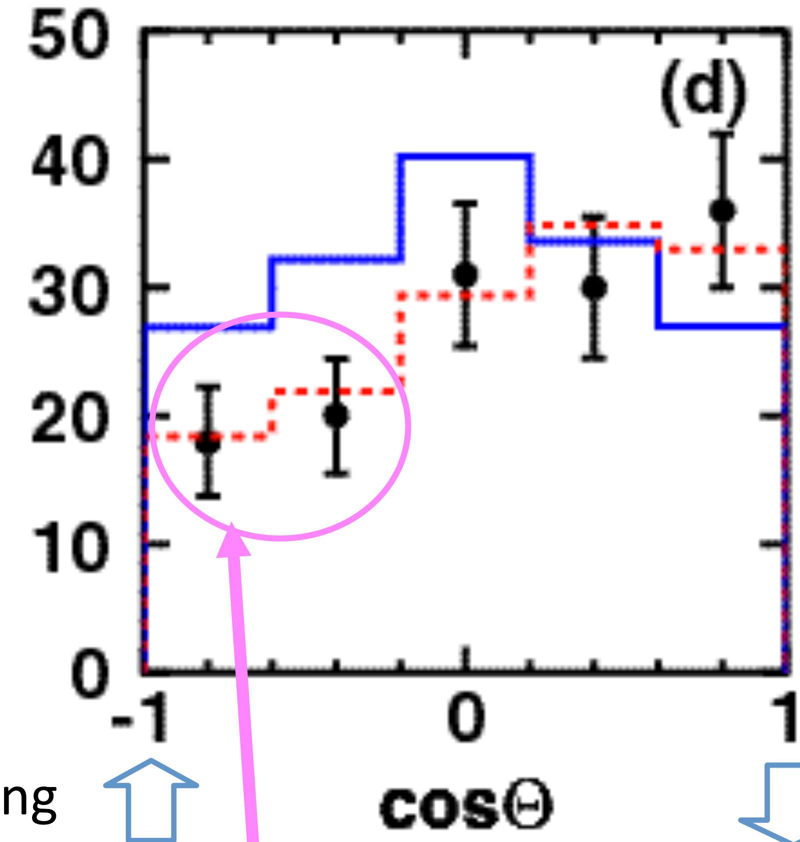
Deficit of upward-going μ-like events

Up/Down=0.58 $^{+0.13}_{-0.11}$ (2.9 σ)

# *Zenith angle distribution (multi-GeV)*

multi-GeV
μ-like
events

Kamiokande PLB 335, 237 (1994)




No oscillation

$\nu_\mu \rightarrow \nu_\tau$ (best fit)

Up-going

Down-going

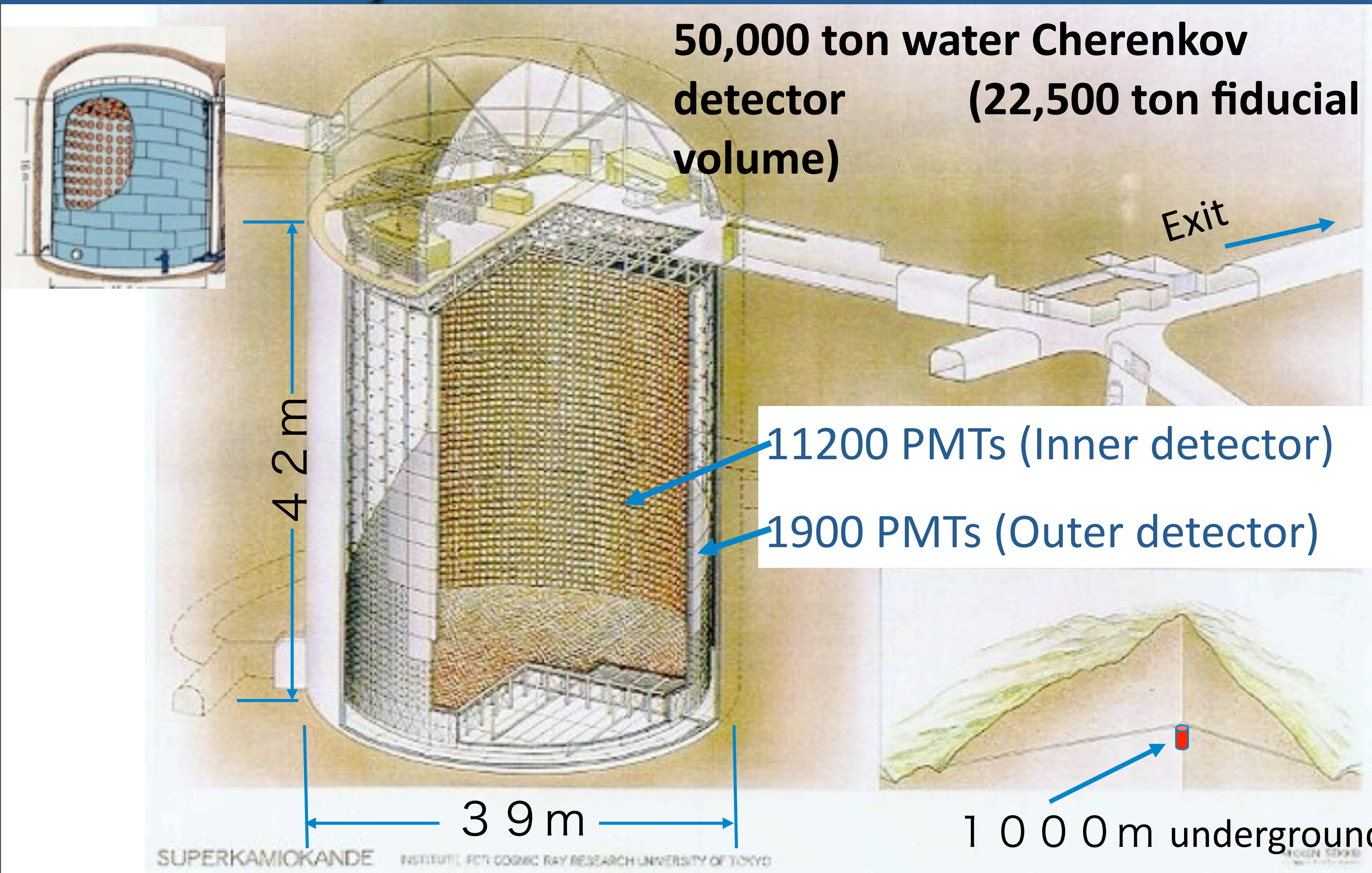
Deficit of upward-going μ-like events

Up/Down=0.58 $^{+0.13}_{-0.11}$ (2.9 σ)

Not high enough statistics to conclude …
Much higher statics required (= much larger detector required)

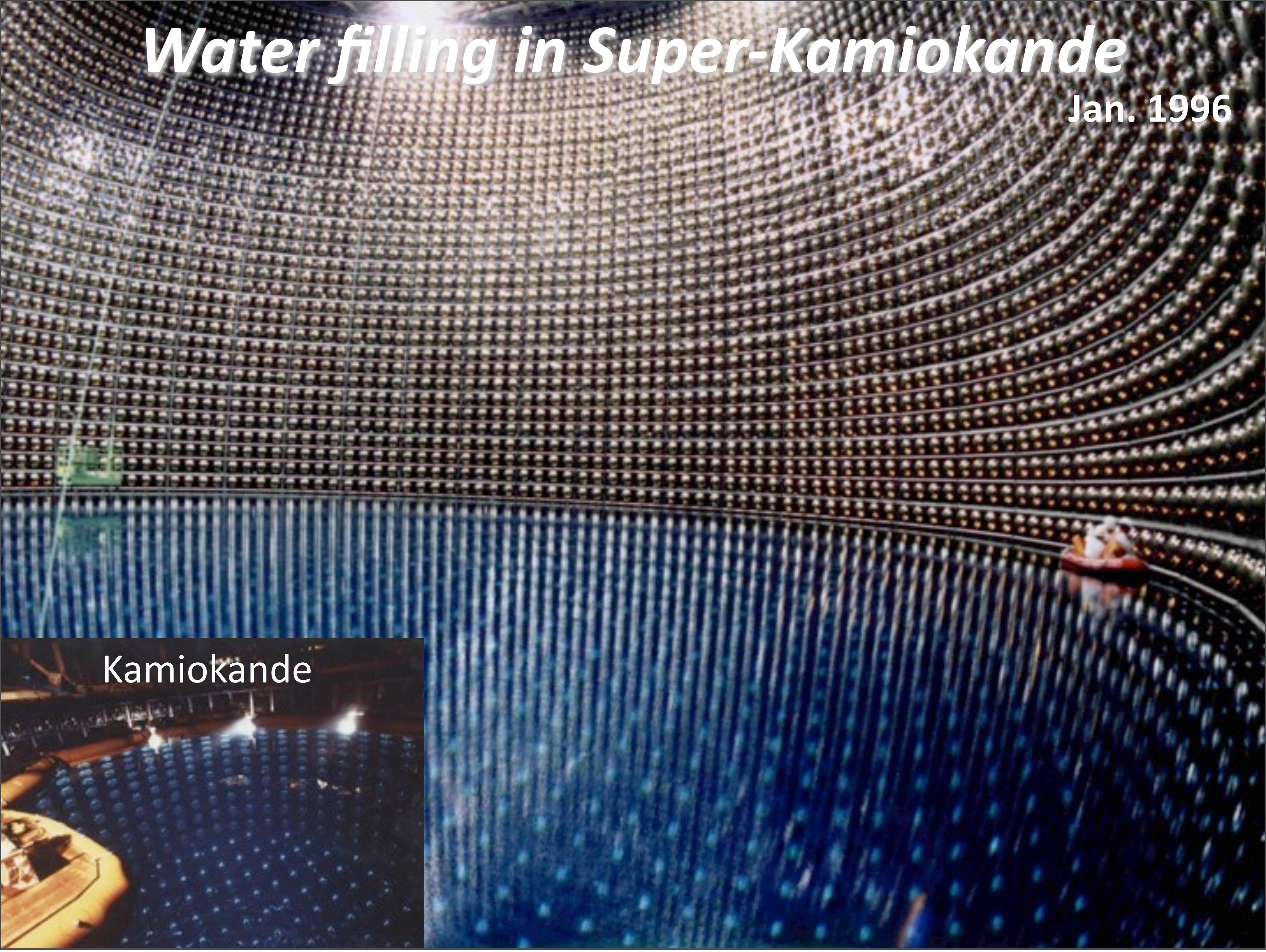
# Super-Kamiokade detector

50,000 ton water Cherenkov detector (22,500 ton fiducial volume)



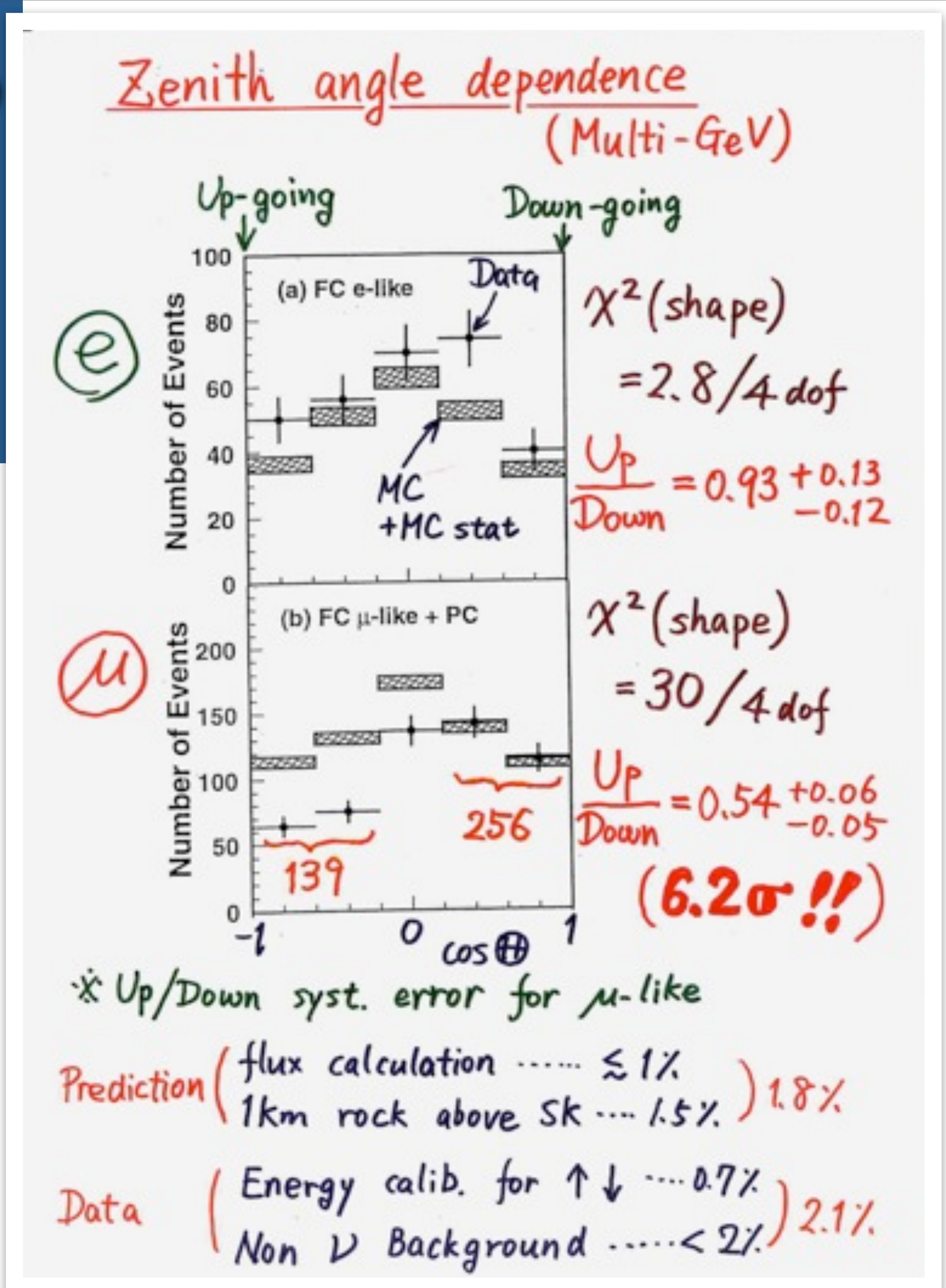

UAM!!

(Prof. L. Labarga's group)


Water filling in Super-Kamiokande
Jan. 1996
Kamiokande

# Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.



# President's remarks at the 1998 MIT commencement

**June 5, 1998**

**REMARKS BY THE PRESIDENT AT MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1998 COMMENCEMENT**

THE WHITE HOUSE

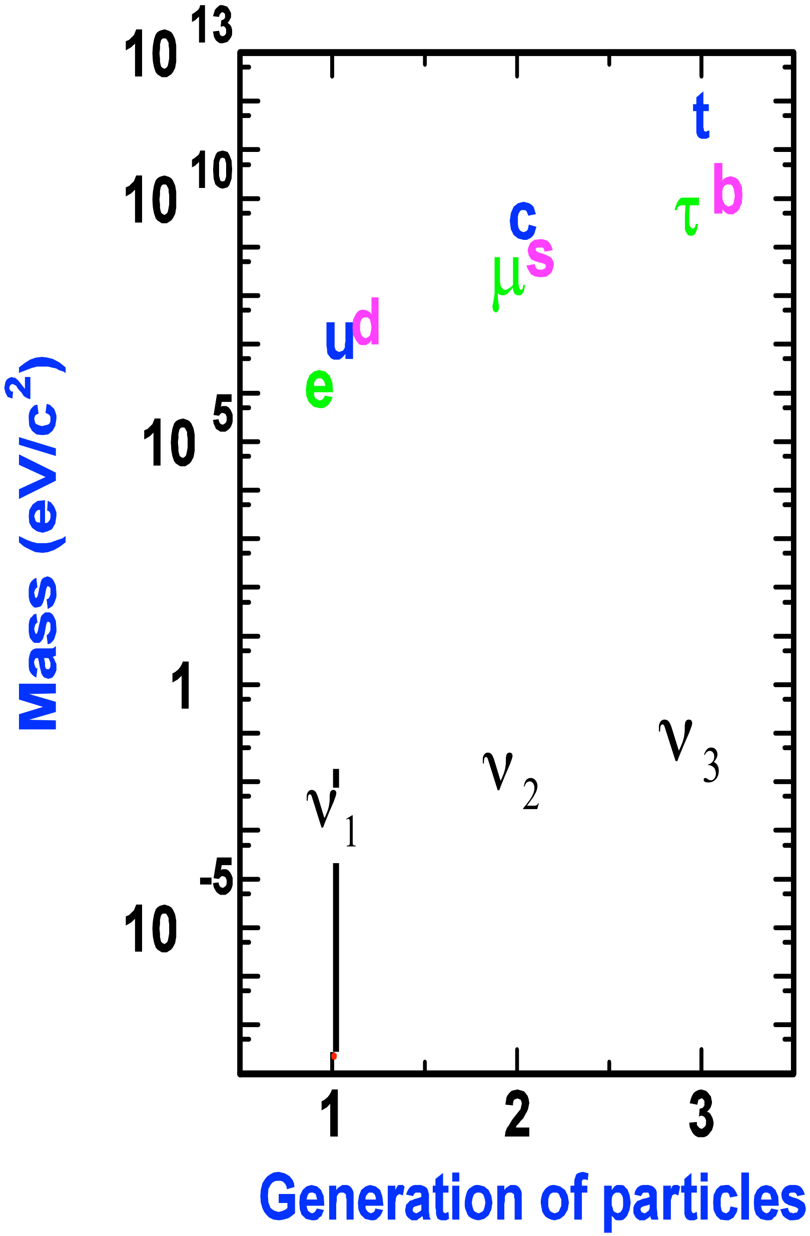
Office of the Press Secretary
(Lincoln, Massachusetts)

For Immediate Release June 5, 1998

First, we must help you to ensure that America

continues to lead the revolution in science and technology. Growth is a prerequisite for opportunity, and scientific research is a basic prerequisite for growth. Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories -- from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands.

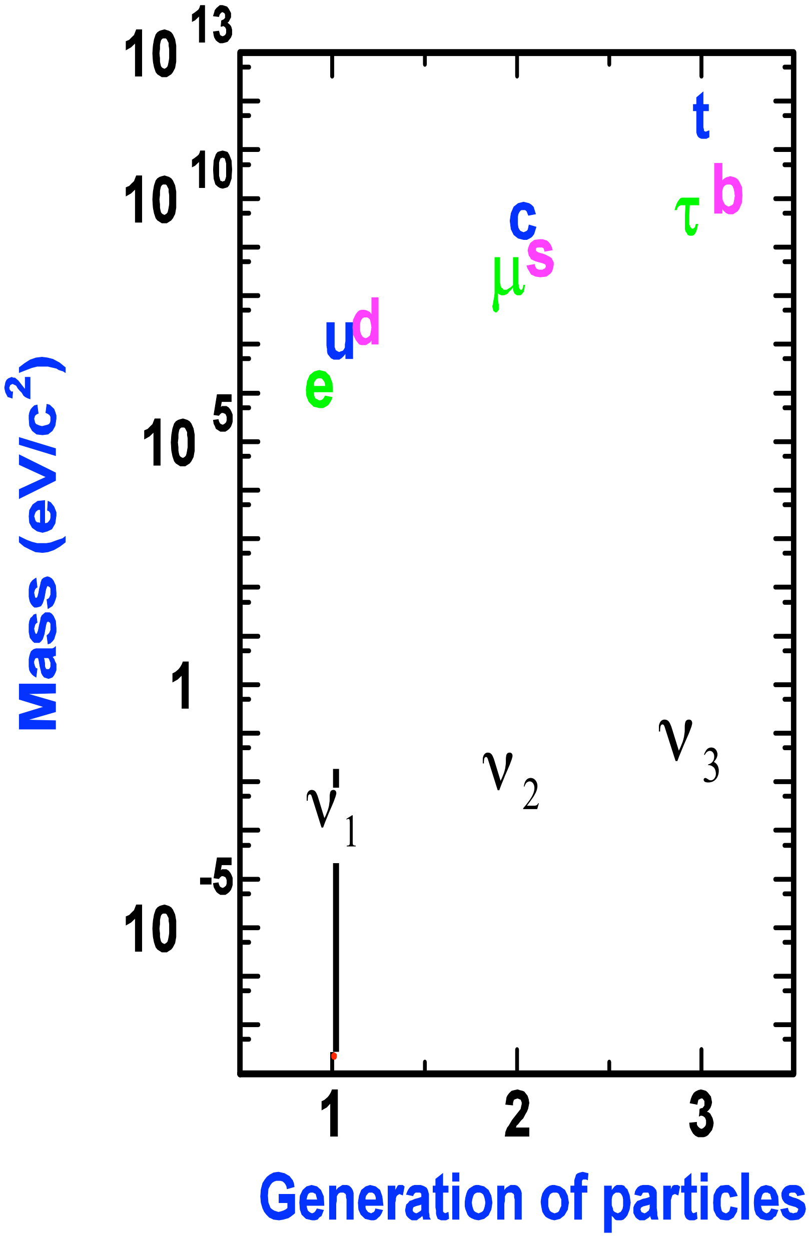
# Why very small neutrino masses are important?




$$\left(\frac{m(\nu_3)}{m(top\ \ quark)}\right) \approx \left(\frac{1}{3\times10^{12}}\right)$$

$$m_\nu \approx \frac{m_q^2}{m_N}$$

# Why very small neutrino masses are important?




$$\left(\frac{m(\nu_3)}{m(top\ \ quark)}\right) \approx \left(\frac{1}{3\times 10^{12}}\right)$$

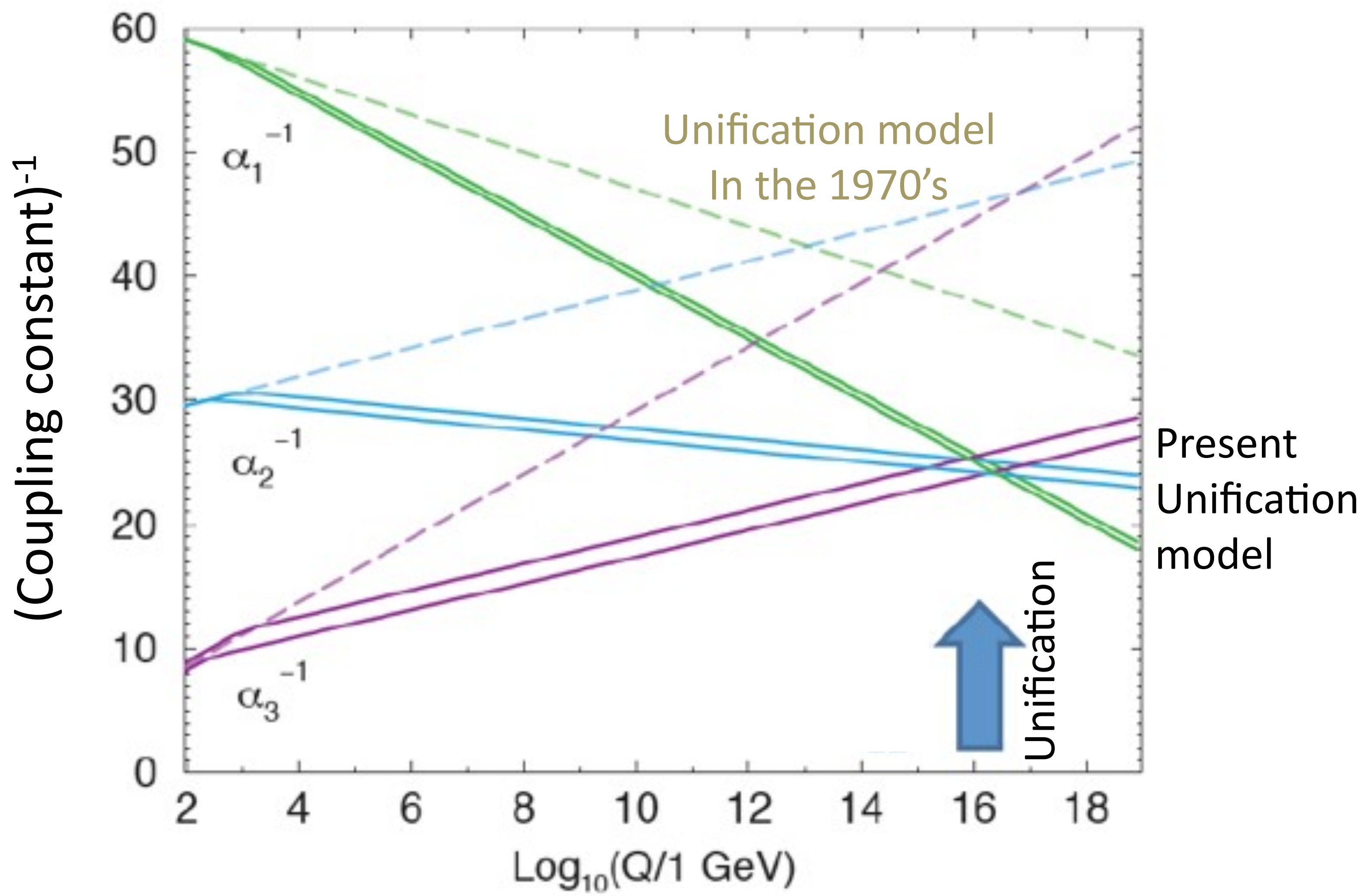
See-Saw mechanism

Minkowsky, Yanagida,
Gell-mann, Lamond, Slansky

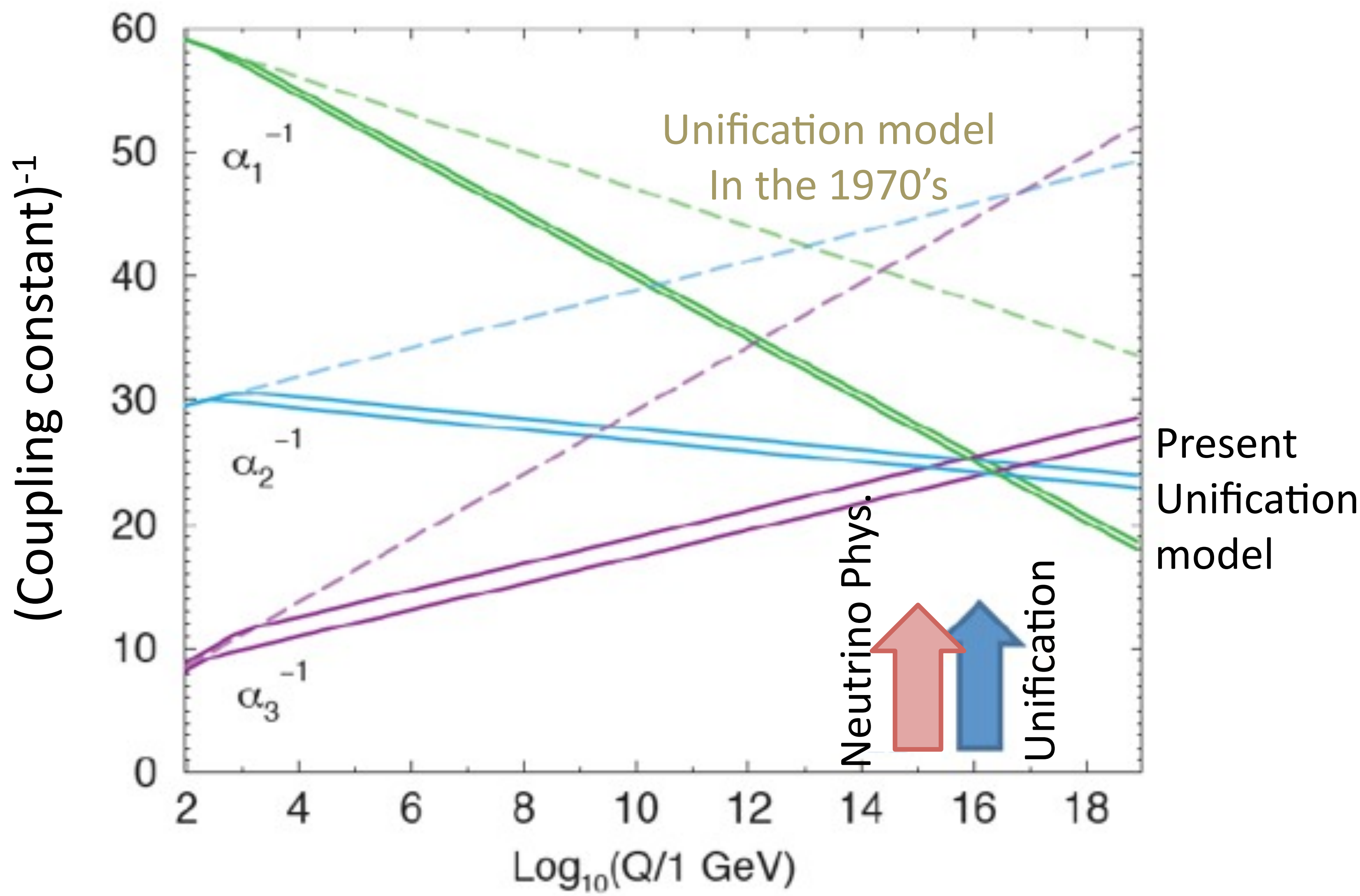
$$m_\nu \approx \frac{m_q^{\ 2}}{m_N}$$

If we input $m_{\nu 3}$ and $m_q$ ($m_{top}$ is used), we get $m_N = 10^{15}$GeV

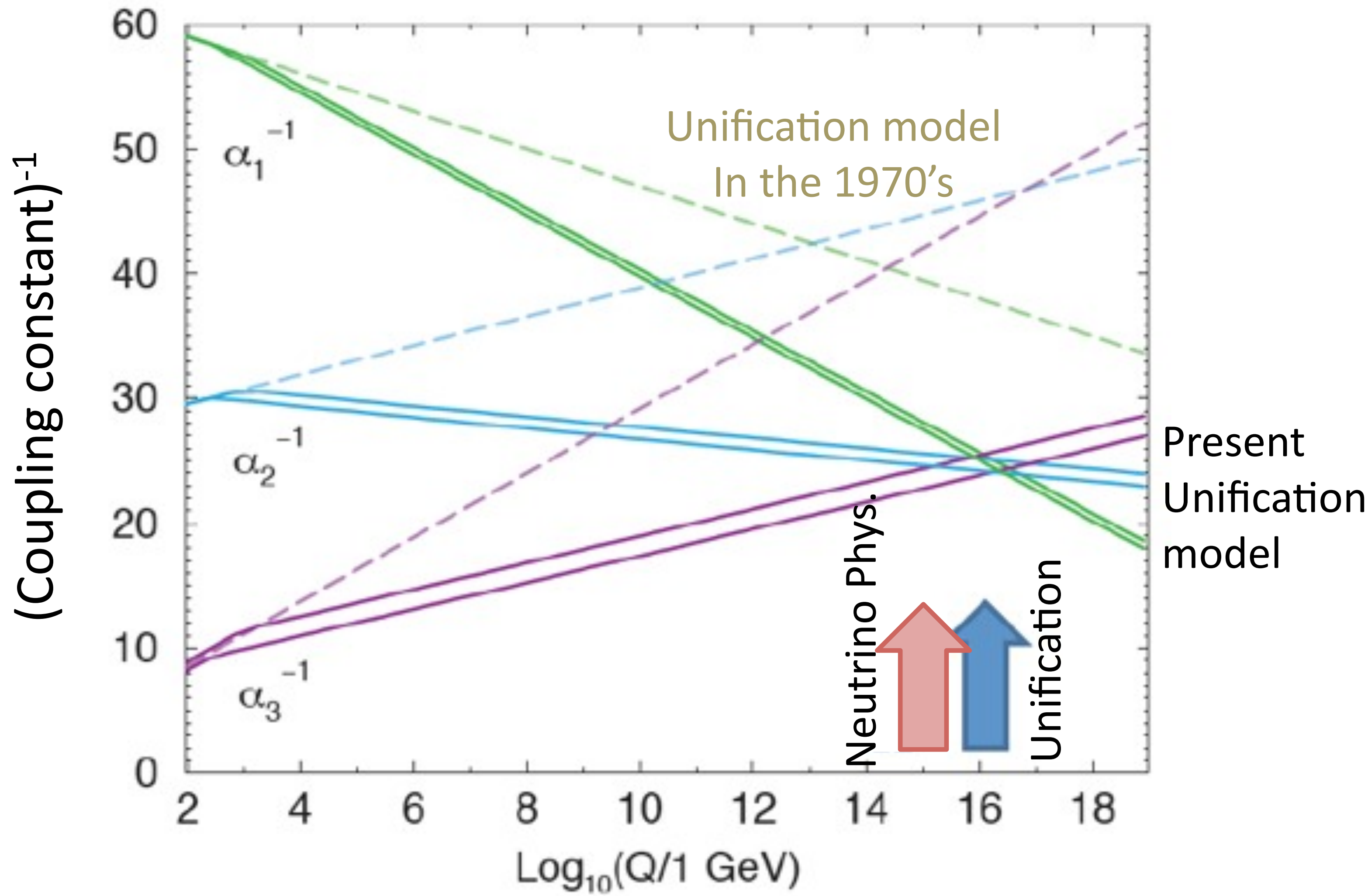
# *Mass scales of neutrino physics and Unification*



# *Mass scales of neutrino physics and Unification*

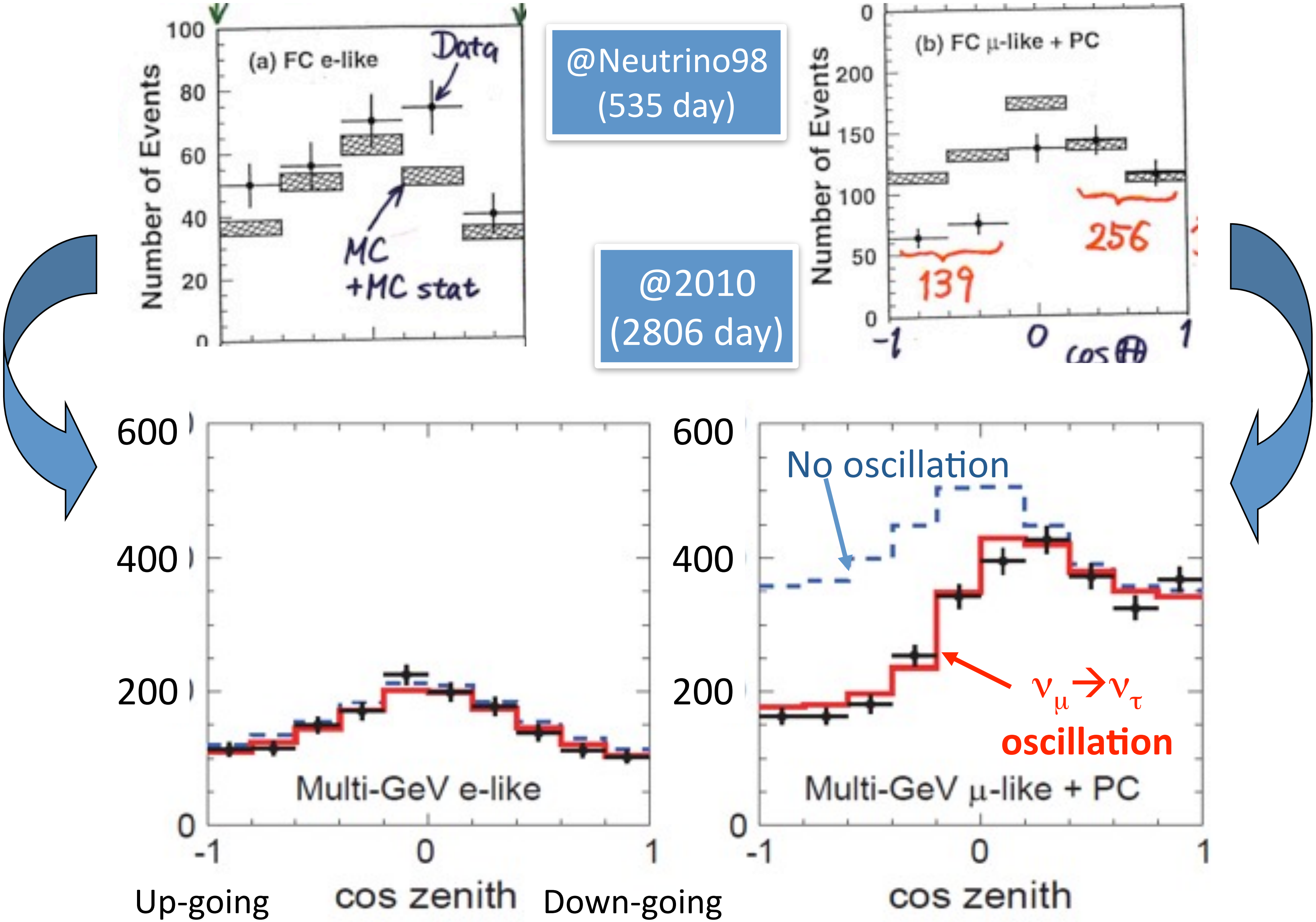


# *Mass scales of neutrino physics and Unification*



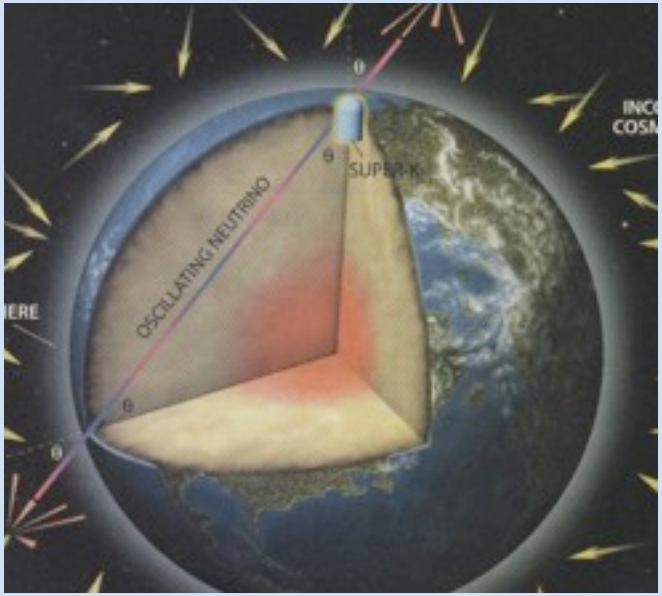

This suggests that physics of neutrino mass could be related to physics of Grand Unification!

# Super-Kamiokande data now



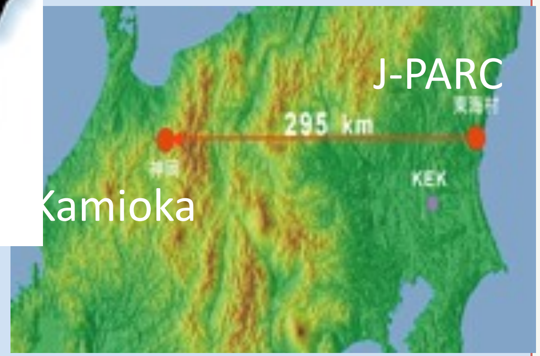
# *Future direction*

## Atmospheric neutrinos




- ➔ Very wide neutrino flight length
- ➔ Wide neutrino energy
- ➔ Mixture of $\nu_\mu$, anti-$\nu_\mu$, $\nu_e$ and anti-$\nu_e$

## Long baseline Experiments


Kamioka

- ➔ Single flight length
- ➔ Controlled neutrino energy
- ➔ almost pure $\nu_\mu$ (or anti-$\nu_\mu$)

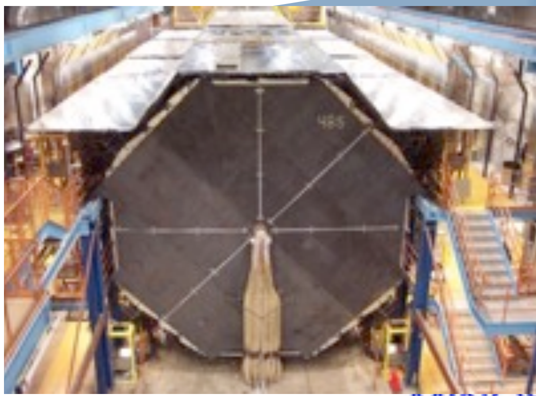
*Initial discovery* ➔ *Precise studies*

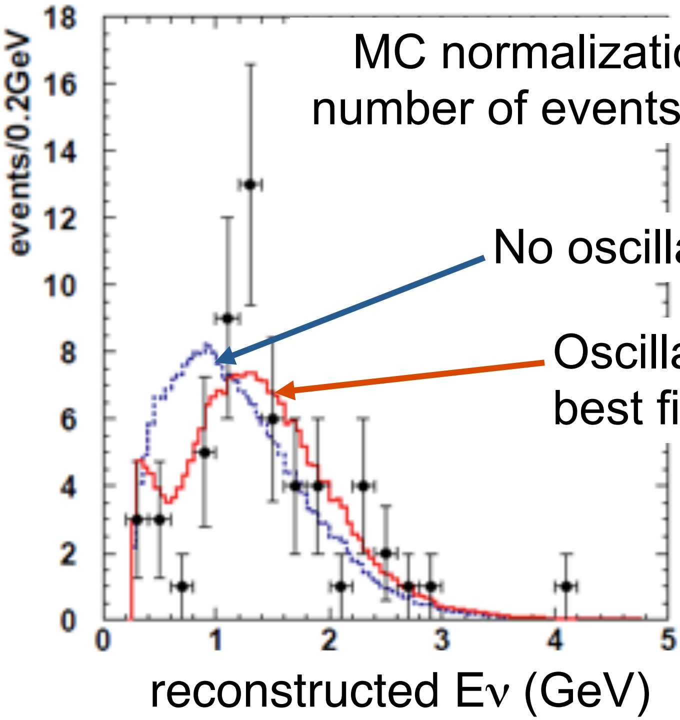
(However, there are still topics that atmospheric neutrinos can contribute …)

# LBL experiments

K2K experiment (1999-2004)


MINOS experiment (2005- )

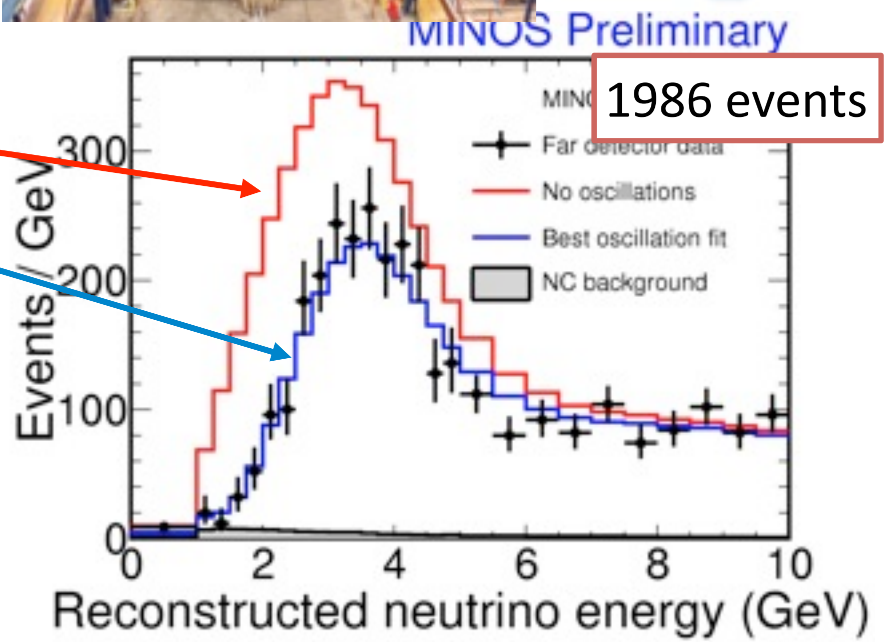



MC normalization:
number of events (58)

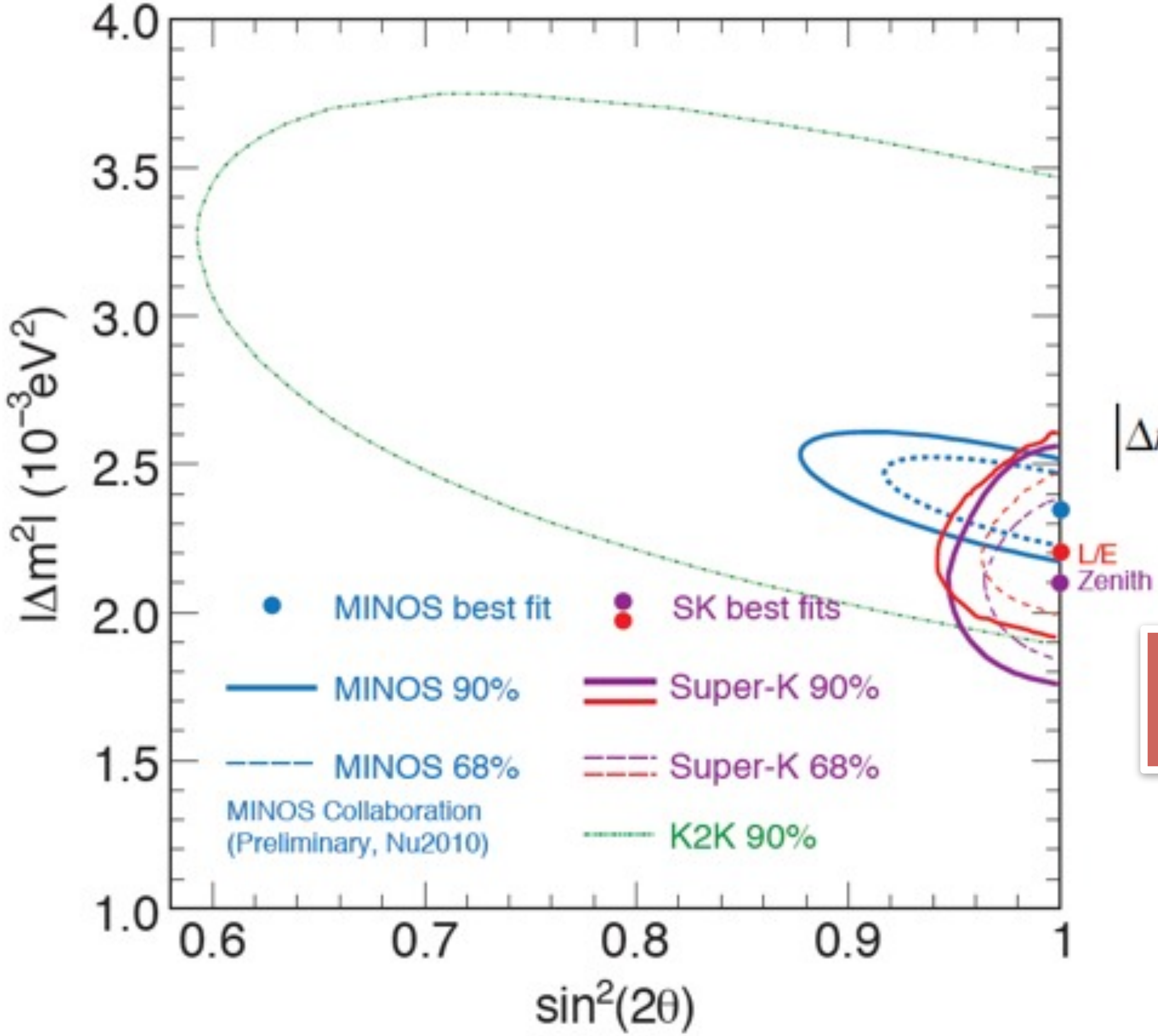
No oscillation

Oscillation
best fit




1986 events

# *Allowed parameter region from atmospheric and long baseline experiments*



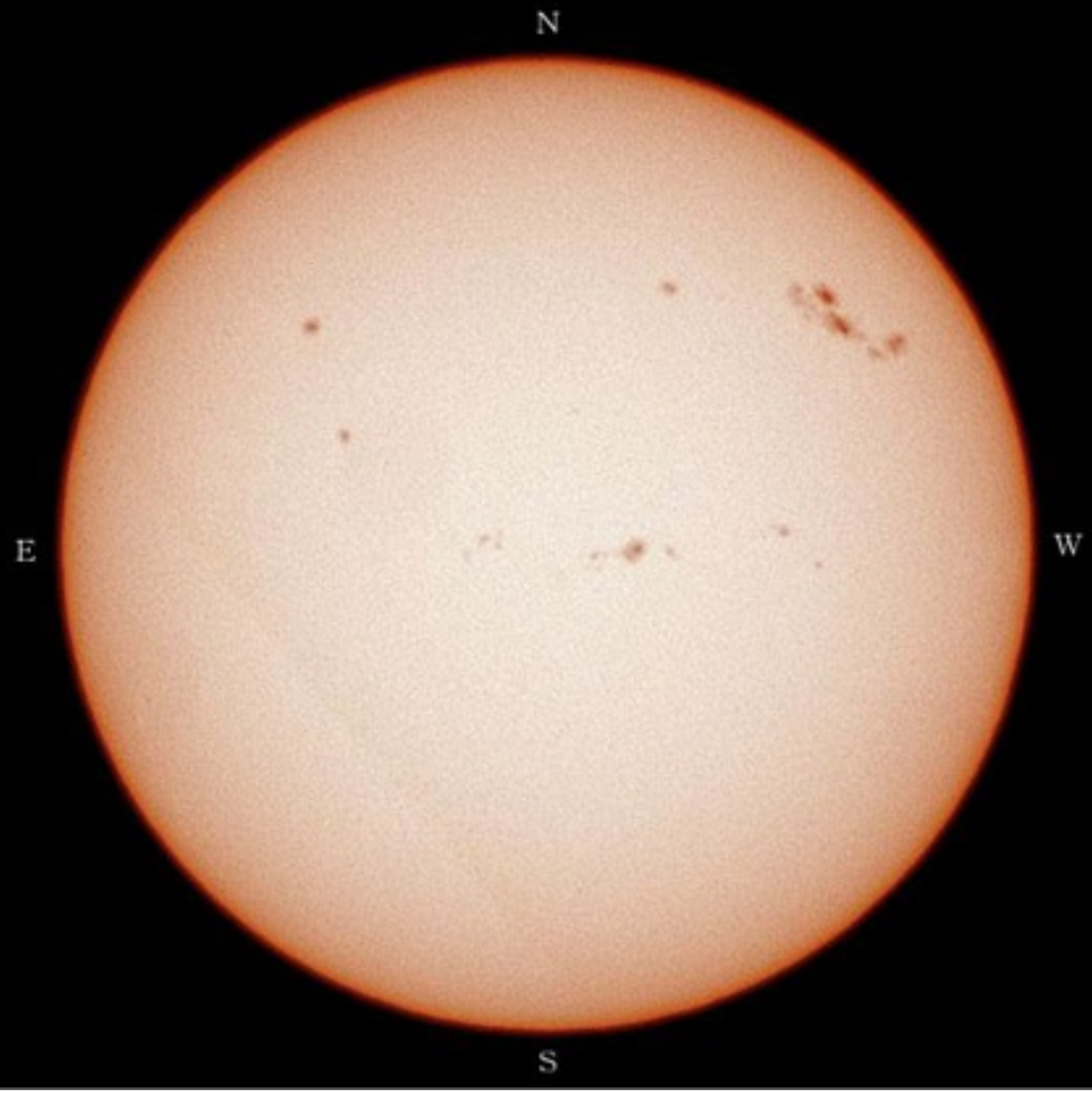

$\nu_3$ might be as heave as 0.05 eV.

$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\text{eV}^2$$

(MINOS)

Consistent with maximal mixing!

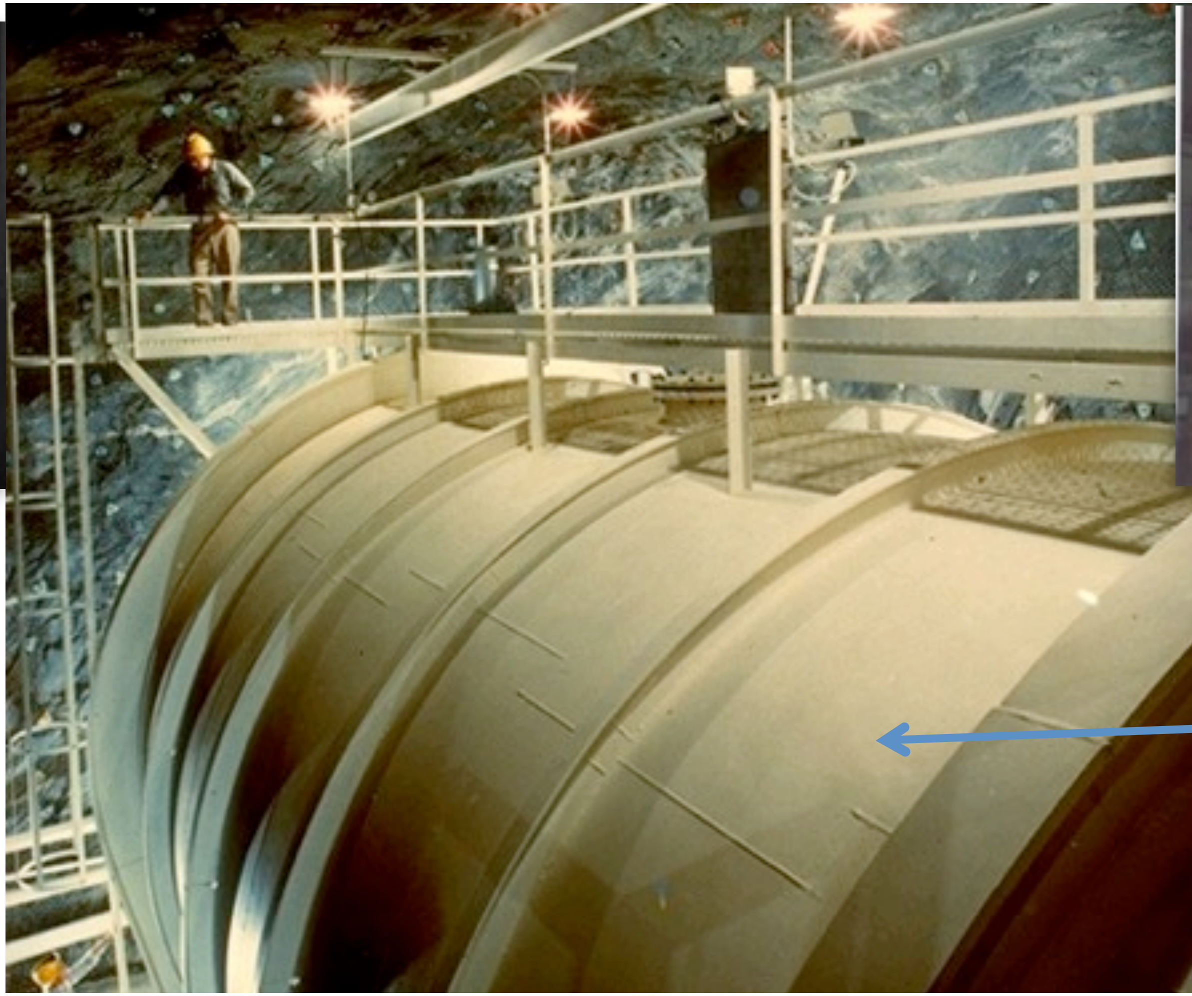
# *Discovery of neutrino oscillations: Part II*



# *Observing the Interior of the Sun with*

J.N. Bahcall “Solar neutrinos I: Theoretical” P.R.L. 12, 300 (1964)
R. Davis Jr. “Solar neutrinos II: Experimental”, P.R.L.12, 303 (1964)

J. N. Bahcall



R. Davis Jr.
(Novel prize 2002)

600ton $C_2Cl_4$

# Solar Neutrino Problem

## Search for Neutrinos from the Sun

R. Davis Jr., D.S. Harmer, and K.C. Hoffman, PRL 20, 1205 (1968)

The Ar production rate by $\nu_e {}^{37}Cl \rightarrow e^- {}^{37}Ar$ was substantially smaller than the prediction by the Standard Solar Model.

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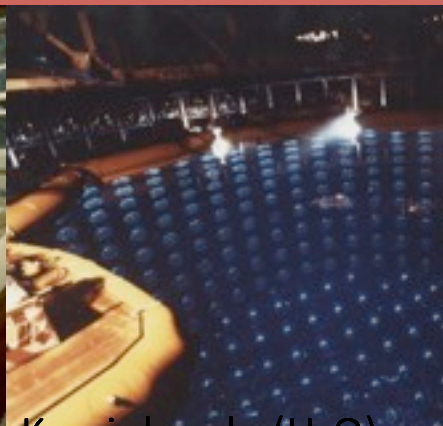
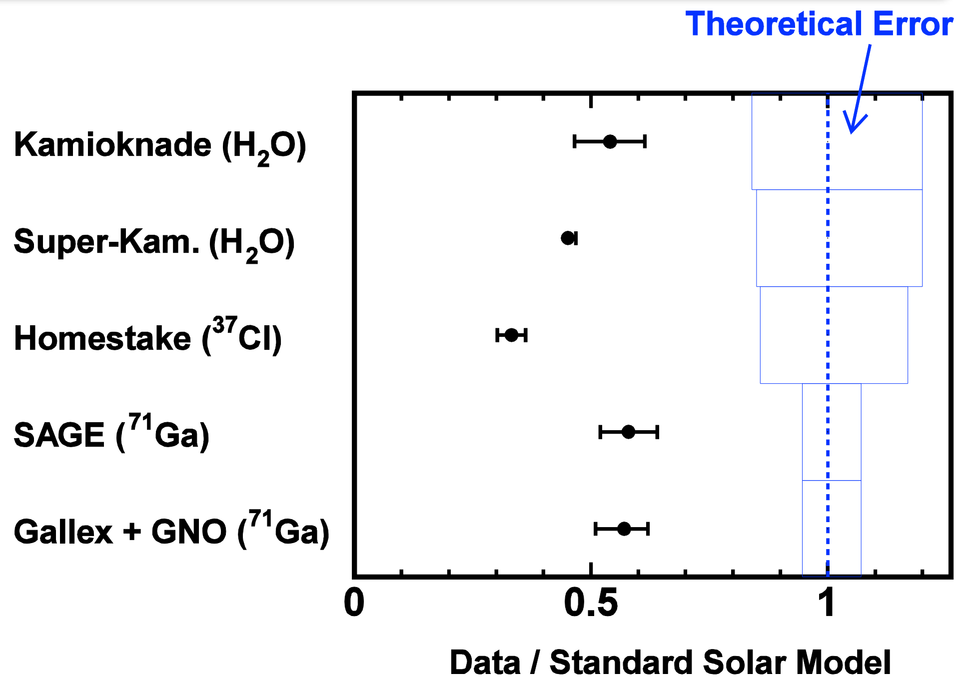
Homestake (Cl)



Kamiokande ($H_2O$)

SAGE (Ga)

Gallex/GNO (Ga)

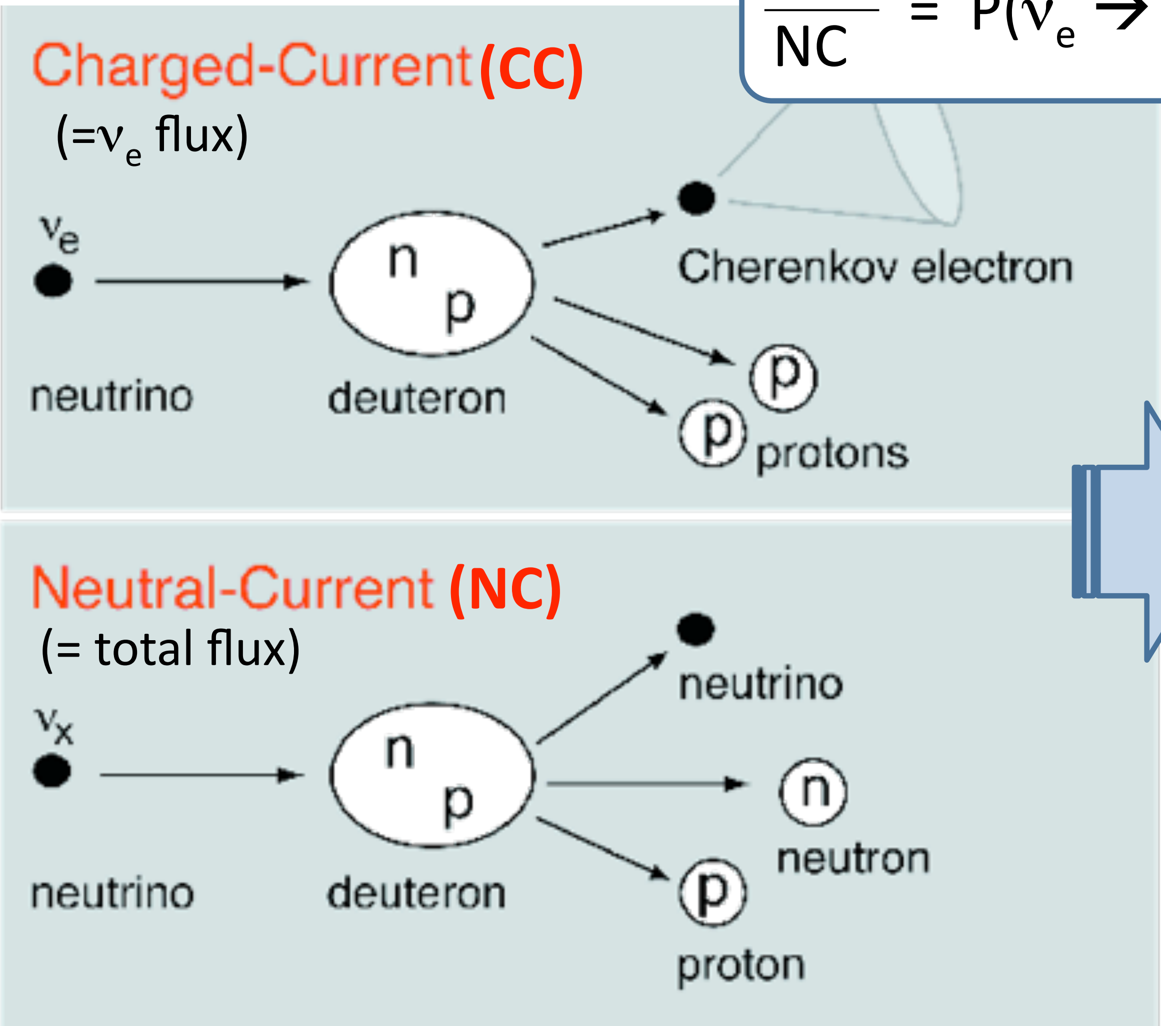


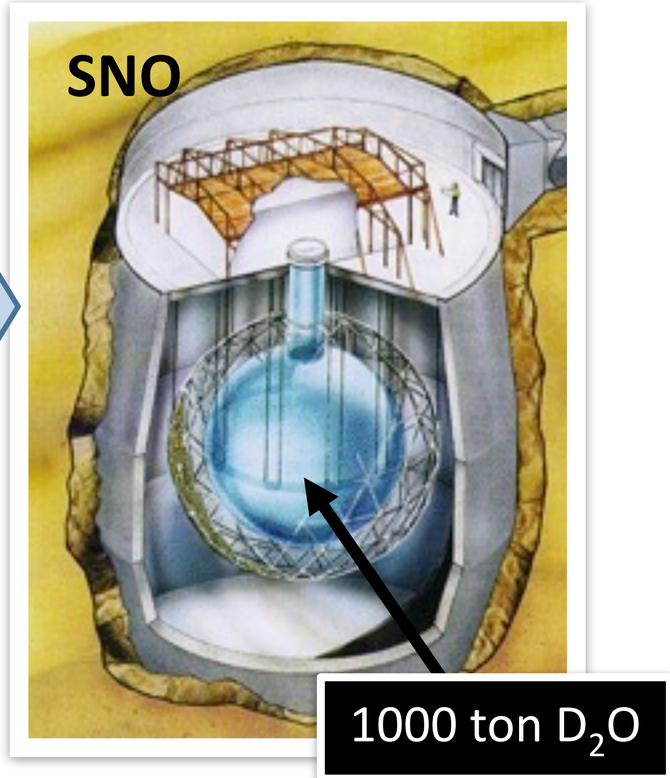

Problem: We did not know the solar neutrino flux very well. People were afraid that the problem might be solved by finding out that the calculated flux was too high...

# *Heavy water experiment*

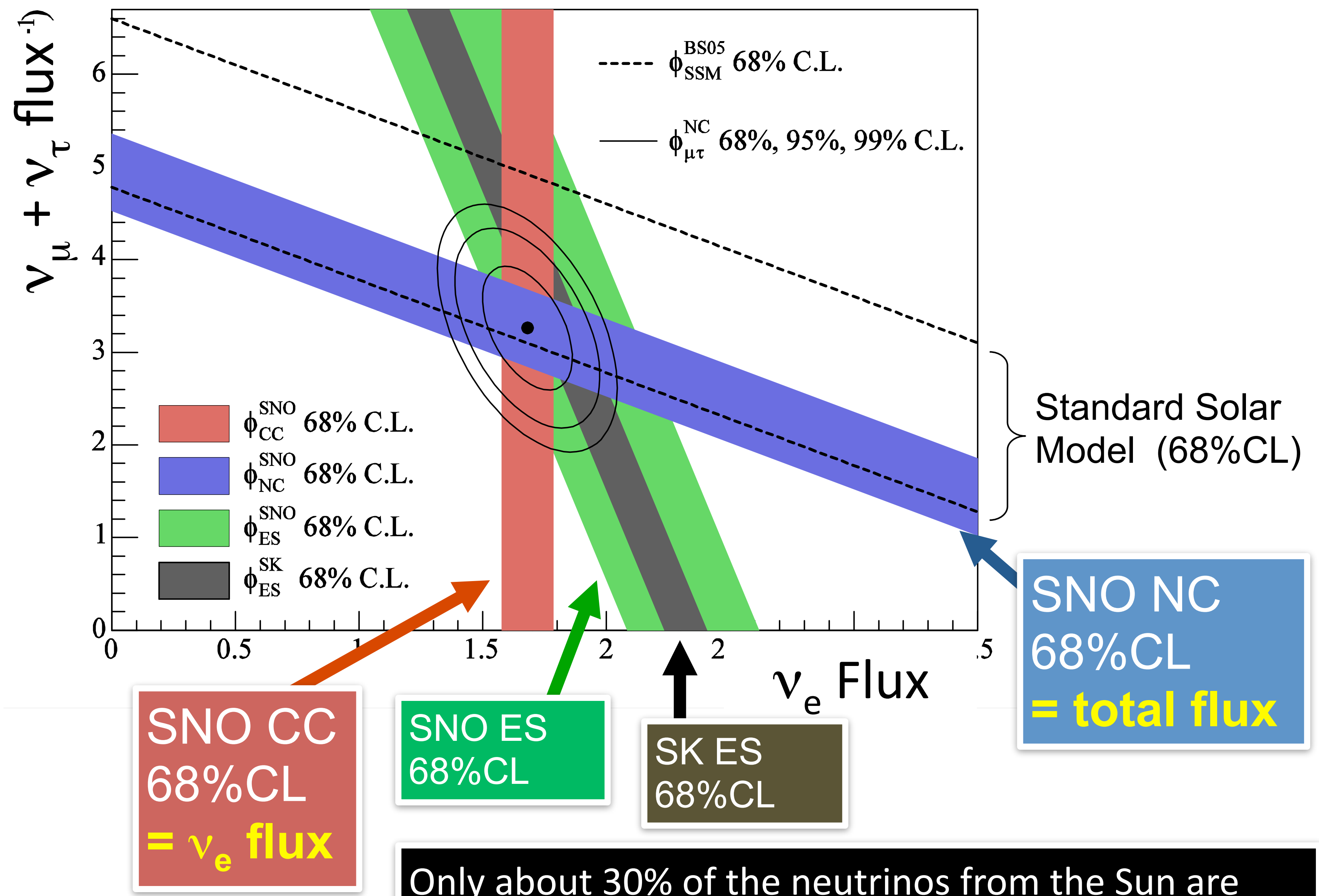
H.Chen PRL 55, 1534 (1985)
"Direct Approach to Resolve the Solar-neutrino Problem"

$$\frac{CC}{NC} = P(\nu_e \rightarrow \nu_e)$$



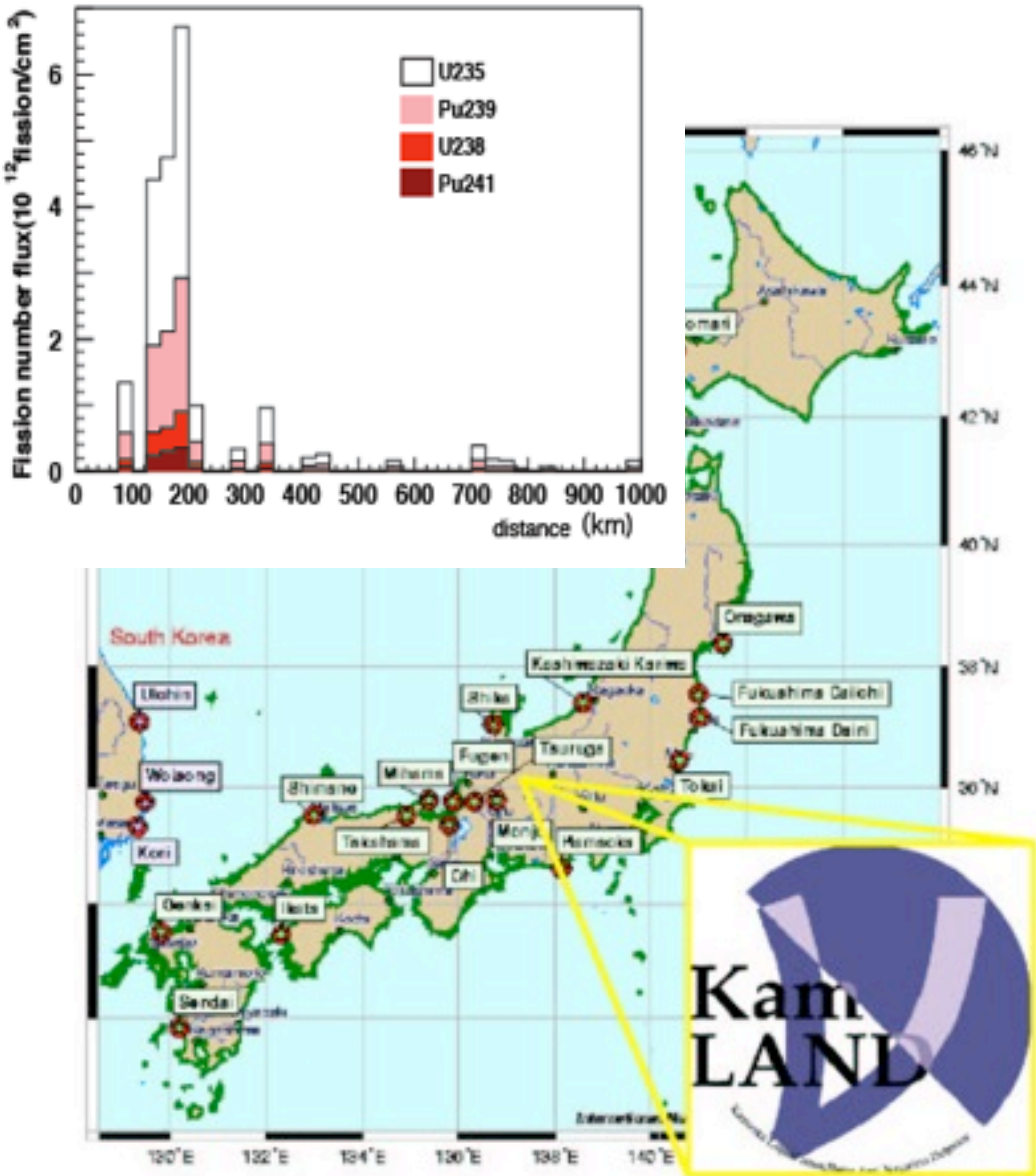



# Solving the solar neutrino problem




Only about 30% of the neutrinos from the Sun are electron-neutrinos! (2001, 2002)

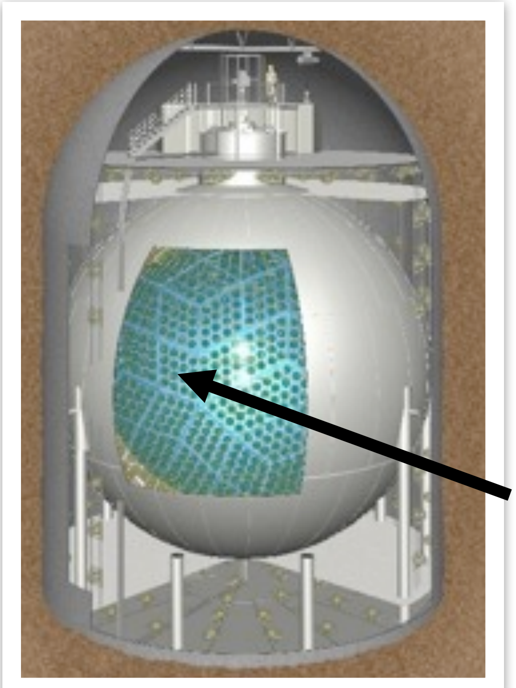
# Long baseline reactor exp: KamLAND




$$\langle L_\nu \rangle = 180km$$
$$\langle E_\nu \rangle = a \ \ few \ MeV$$

Sensitive to $\Delta m^2 > 10^{-5} eV^2$

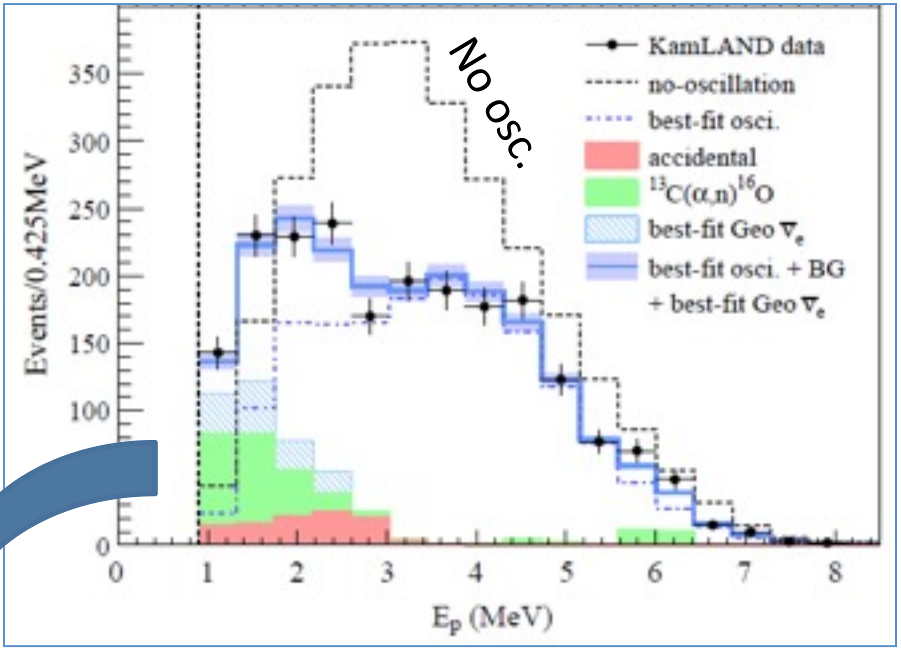
KamLAND

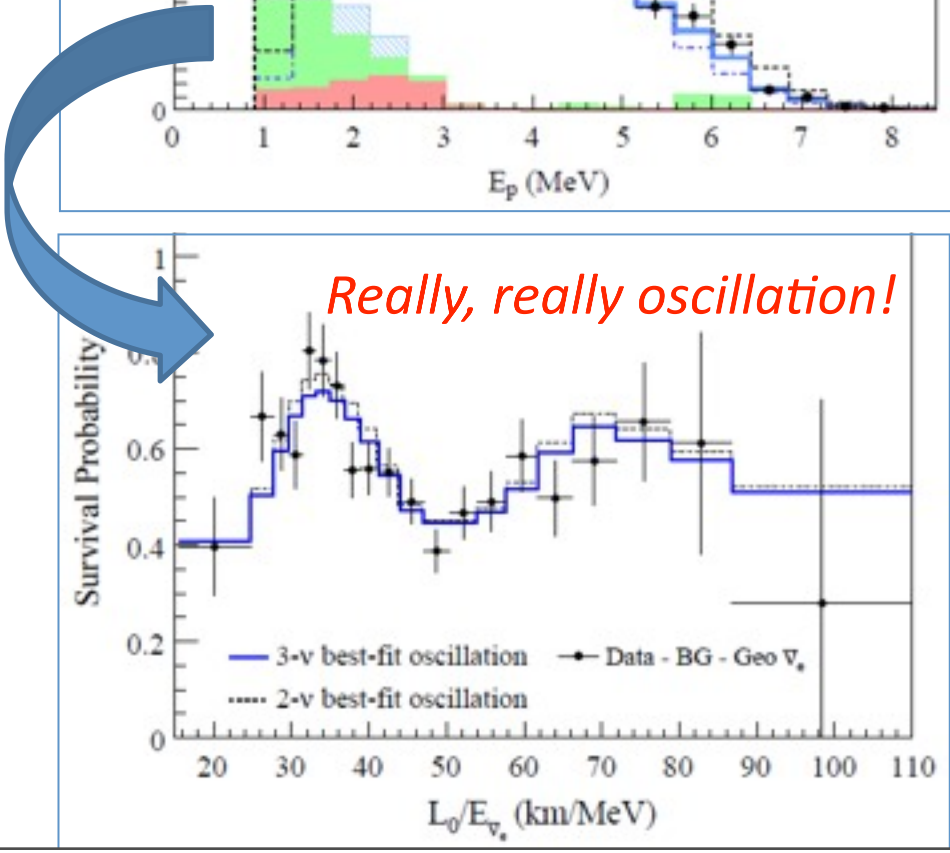


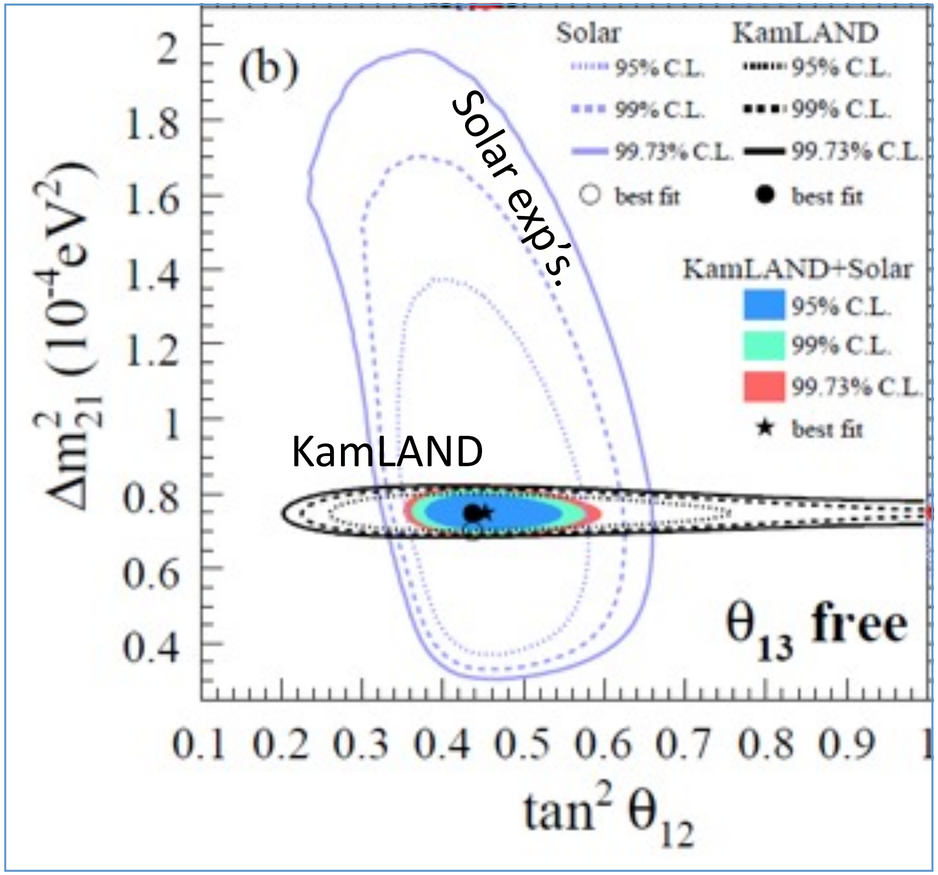
1000 ton liquid scintillator

# *KamLAND and neutrino oscillation*

KamLAND arXiv: 1009.4771



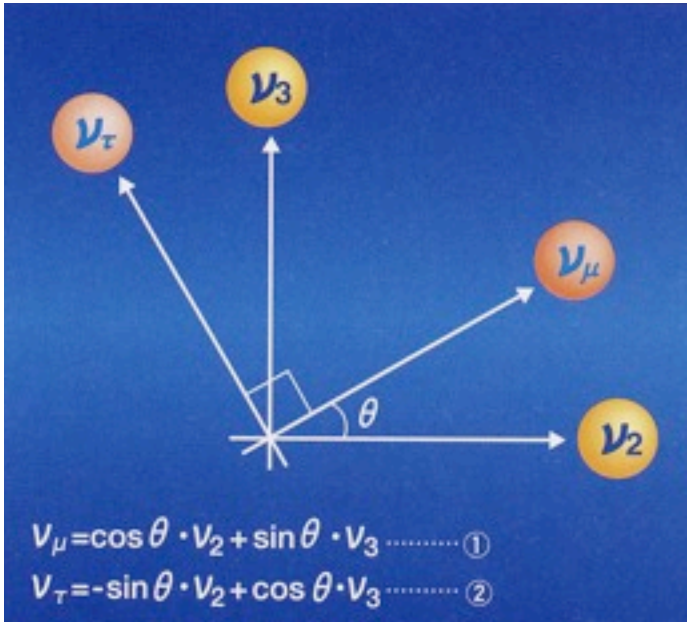




$$\tan^2\theta_{12} = 0.452^{+0.035}_{-0.033},$$
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$$

# *Future prospects*

# Present and future

## Present




*2 flavor neutrino oscillation*:

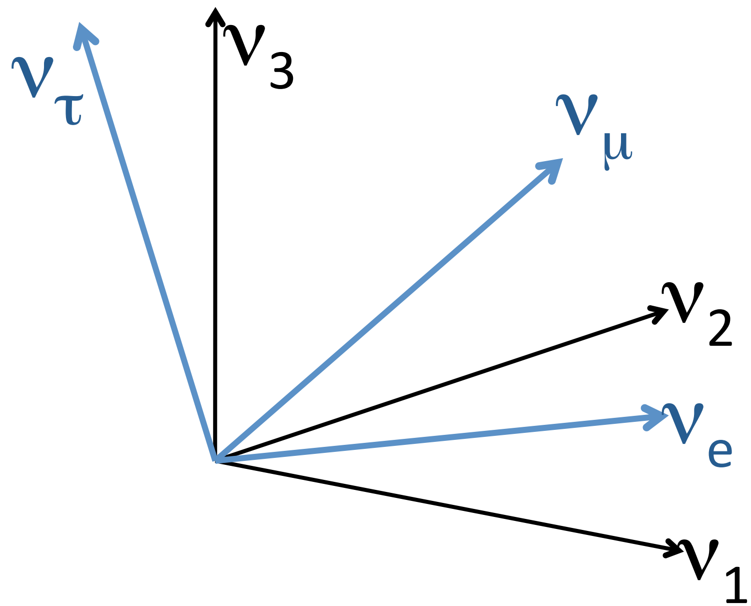
- ◆ $\nu_\mu \Leftrightarrow \nu_\tau$ : atmospheric ν

  accelerator ν

- ◆ $\nu_e \Leftrightarrow \nu_x$ : solar ν

  reactor ν

## Future




*3 flavor neutrino oscillation*:

- ◆ measure 3 mixing angles (2 are known)

∅ measure all the parameters relevant to osc.

# *Matter elementary particles*

# Matter elementary particles


Grand Unification: Unification of forces

# *Matter elementary particles*


Grand Unification: Unification of forces

Unification of quarks and leptons

# Relation between quarks and leptons ?

**Quark mixing**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \times \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

3×3 mixing matrix

**Neutrino mixing**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{MNSP} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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$$V_{CKM} \approx U_{MNSP} \ ?$$

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***For quarks***

$\theta_{12}=13^{o}$

$\theta_{23}=2.4^{o}$

$\theta_{13}=0.21^{o}$

***For neutrinos***

$\theta_{12}=34\pm1^{o}$

$\theta_{23}=45\pm6^{o}$

$\theta_{13} <11^{o}$

Very different!

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$\theta_{12}$=34±1°

$\theta_{23}$=45±6°

$\theta_{13}$ <11°

Very different!

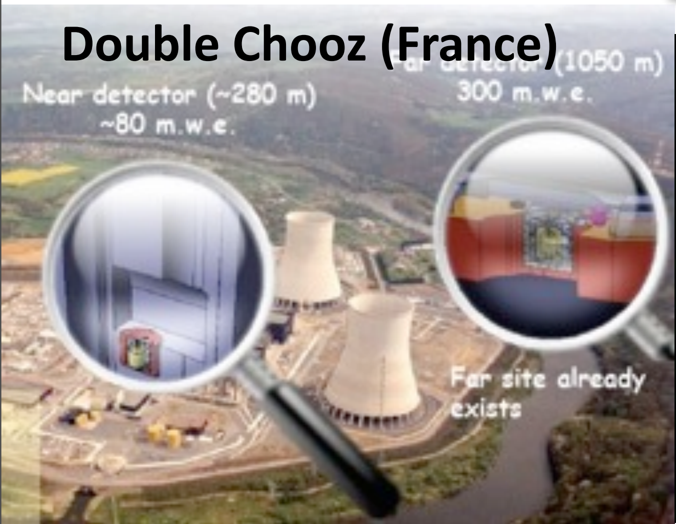
Is $\theta_{23}$ maximal ?

How small is $\theta_{13}$?

# $\theta_{13}$ *experiments*

## Reactor experiments

### Double Chooz (France)

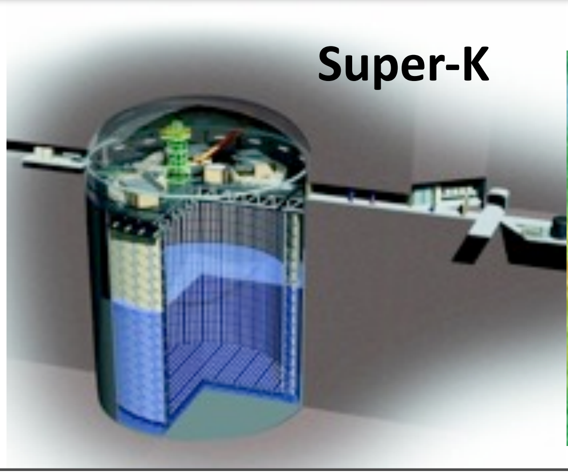



### Daya Bay (China)


### RENO (Korea)

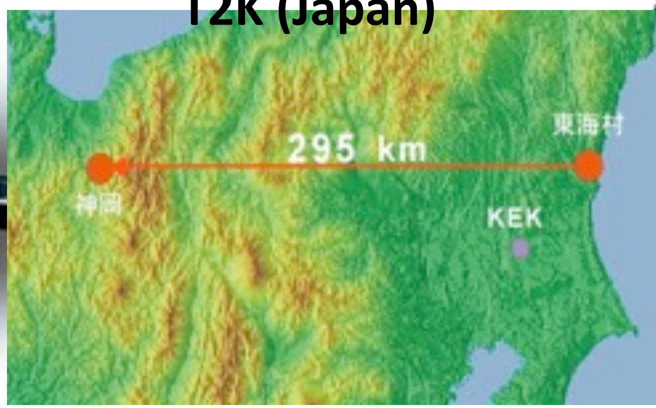
## Atmospheric neutrino exp.

### Super-K

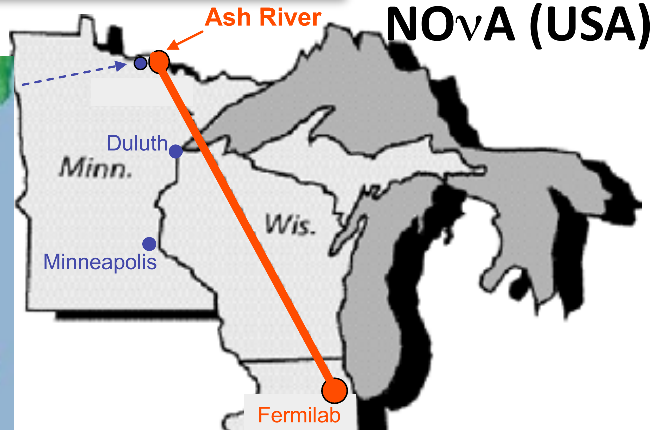


## Long baseline experiments

### T2K (Japan)



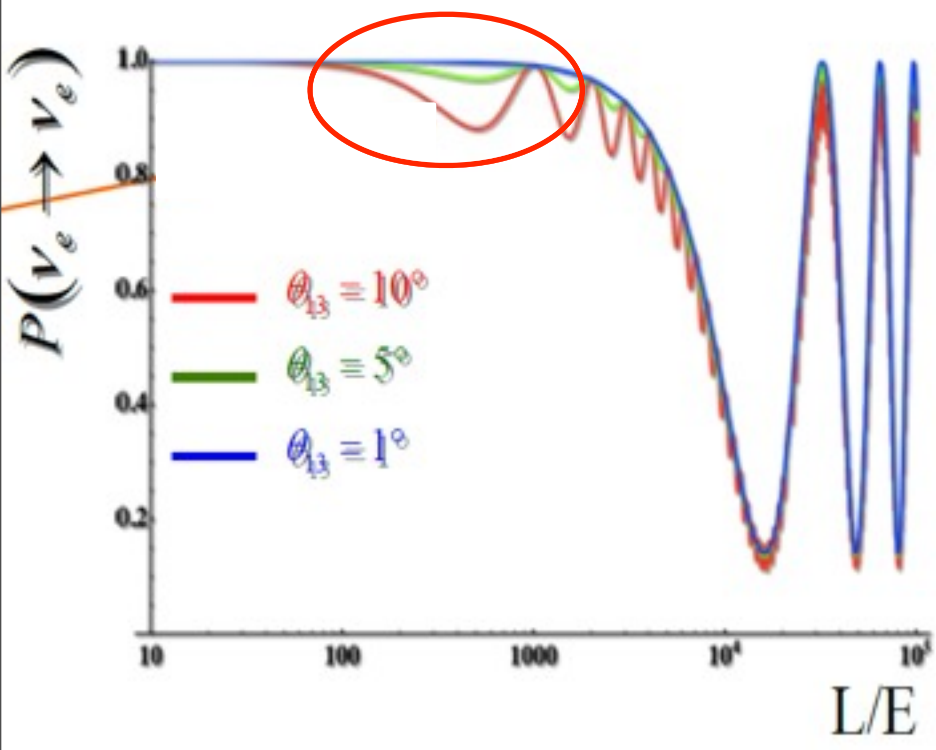

### NOνA (USA)



# Expected non-zero $\theta_{13}$ signals

Reactor experiments

Signal : $\nu_e$ (= electron) disappearance



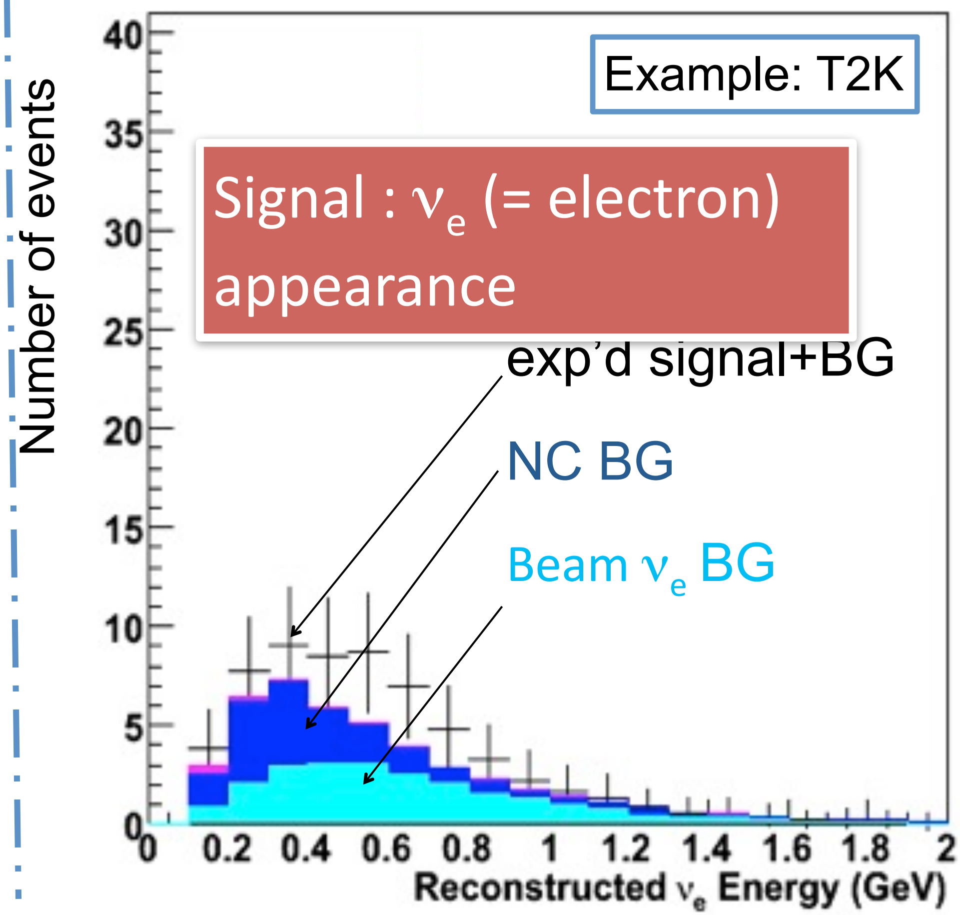

Long baseline experiments

Assume: $\sin^2 2\theta_{13}$=0.01

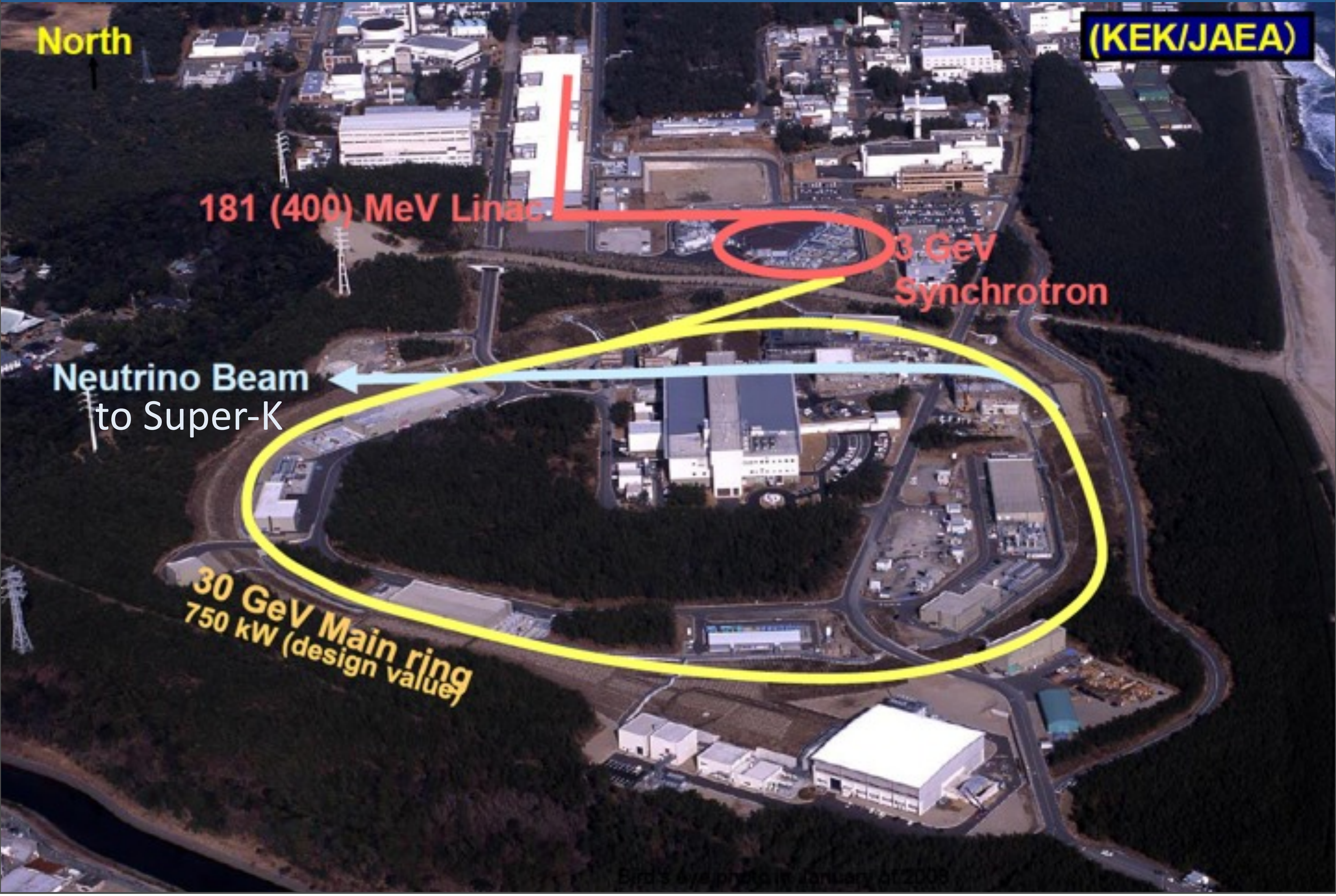
(about 1/15 of the present limit)

Example: T2K

Signal : $\nu_e$ (= electron) appearance



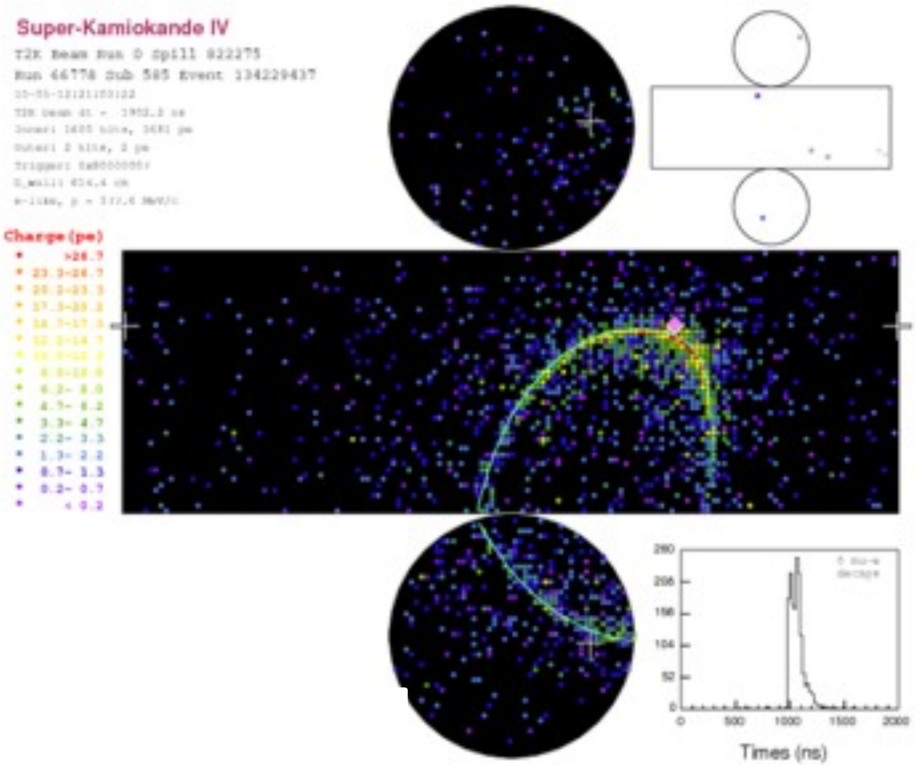
# J-PARC and the T2K beam line



# *Initial T2K results on electron appearance*

Data until the 2010 summer shutdown were analyzed. ($3.23\times10^{19}$ POT)

1 electron candidate




| Expected background | |
|---|---|
| $\nu\mu$ | 0.13 NC 95% |
| anti-$\nu\mu$ | 0.01 |
| $\nu e$ | 0.16 |
| Total | 0.30 ± 0.07 (syst) |
| **Signal + background ($\sin^2 2\theta_{13}$=0.1)** | |
| Total | 1.20 ± 0.22 (syst) |

A. Feldman-Cousins
B. Classical one-sided limit

A

| Hierarchy | Upper Limit | Sensitivity |
|---|---|---|
| Normal ($\Delta m^2_{23} > 0$) | 0.50 | 0.35 |
| Inverted ($\Delta m^2_{23} < 0$) | 0.59 | 0.42 |

B

| Hierarchy | Upper Limit | Sensitivity |
|---|---|---|
| Normal ($\Delta m^2_{23} > 0$) | 0.44 | 0.32 |
| Inverted ($\Delta m^2_{23} < 0$) | 0.53 | 0.39 |

at ($\Delta m_{23}^2$, $\sin^2 2\theta_{23}$, $\delta_{cp}$)=($2.4\times10^{-3}$eV$^2$, 1.0, 0.0)

Nakadaira KEK seminar
Okumura ICRR seminar

# *Earthquake on March 11*

- Super-K and KamLAND were OK.
- People in Tohoku University were OK.
- J-PARC was damaged.

Near LINAC bulding

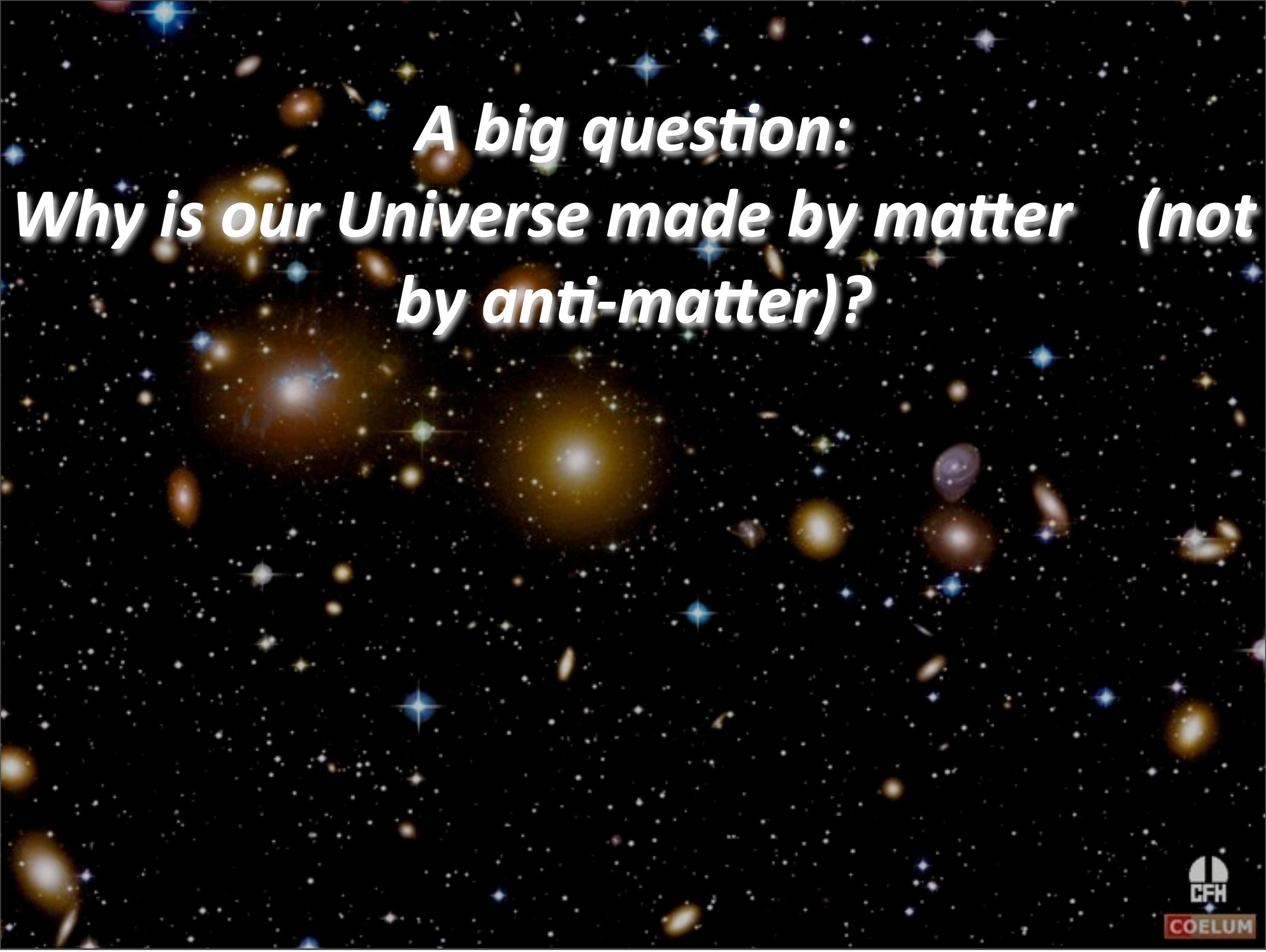
Road Near 3GeV PS

- "Master Plan for J-PARC Recovery" will be released in


CFH
COELUM

# A big question:

# Why is our Universe made by matter (not by anti-matter)?



# A big question:
# Why is our Universe made by matter (not by anti-matter)?

It has been discussed that the origin of matter may come from the particle=anti-particle asymmetric decay of the heavy neutral particle of the See-Saw mechanism.

Fukugita Yanagida PLB 1986

$$m_\nu \perp \frac{m_q^2}{m_N}$$

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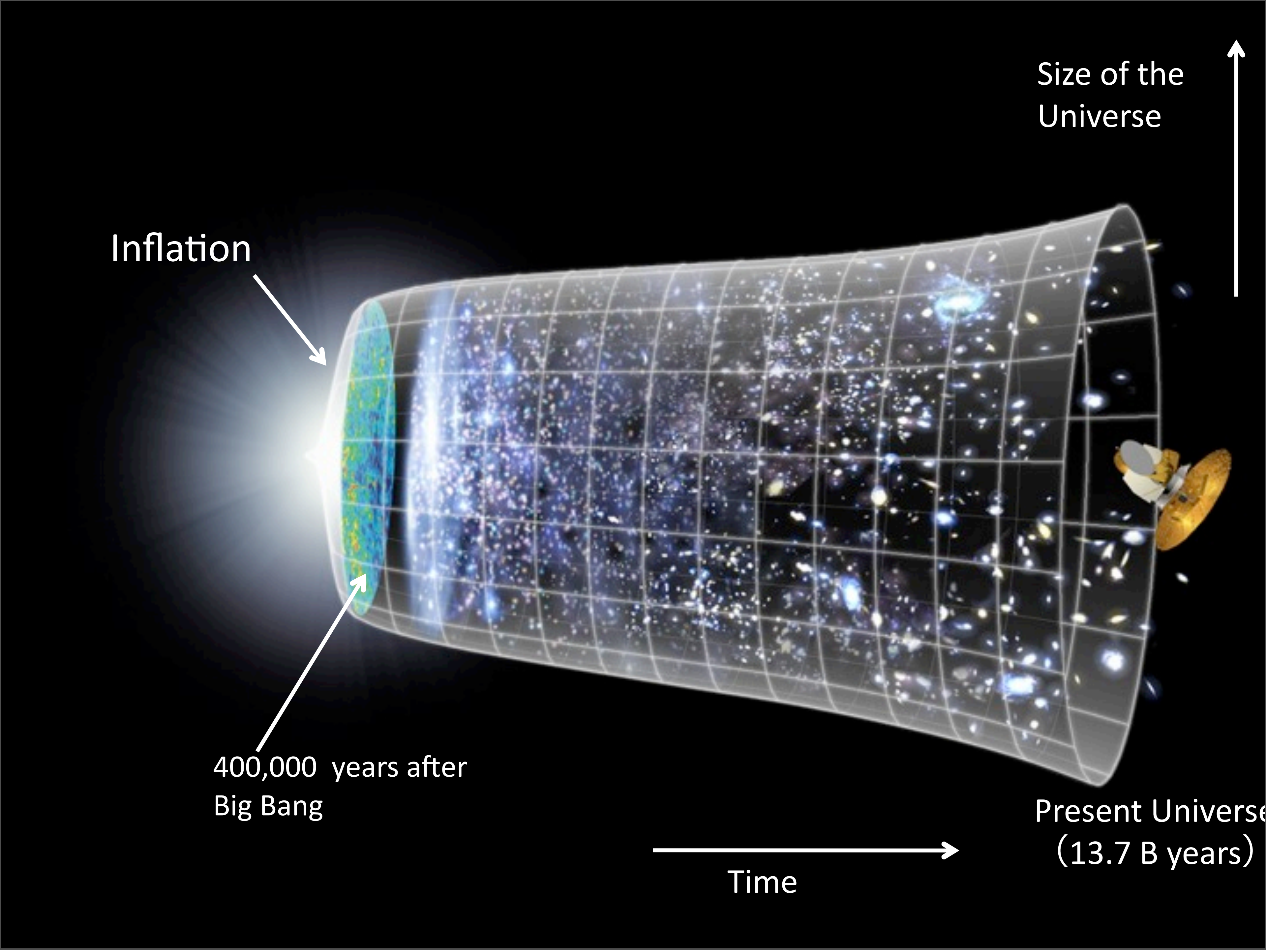
$$m_\nu \perp \frac{m_q^2}{m_N}$$

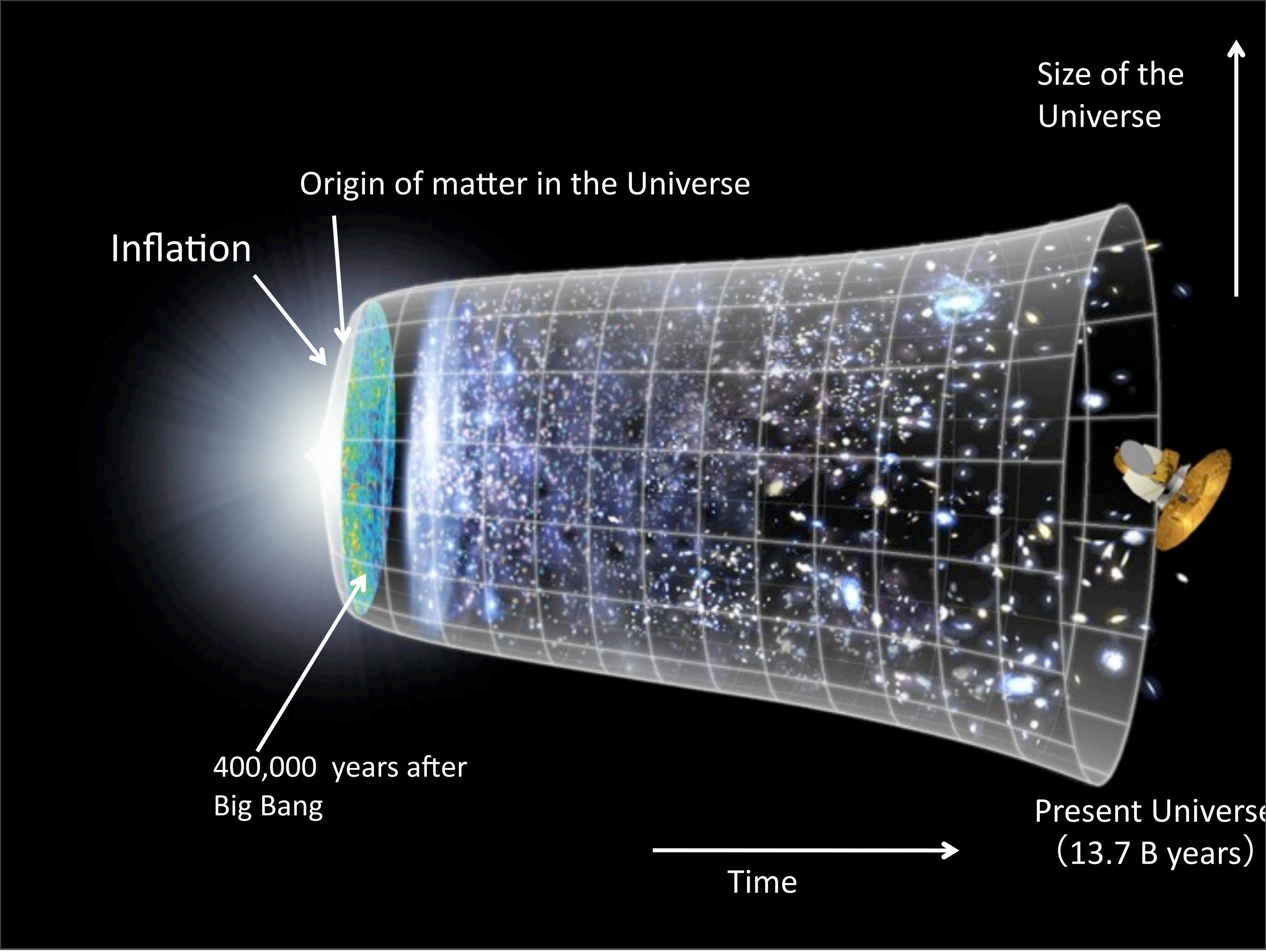
Fukugita Yanagida PLB 1986

➔This idea should be tested.

- ◆ Are neutrino and anti-neutrino oscillations different?

( ◆ Is neutrino its own anti-particle? )


Size of the Universe
Inflation
400,000 years after Big Bang
Present Universe
(13.7 B years)
Time


Size of the
Universe
Origin of matter in the Universe
Inflation
400,000 years after
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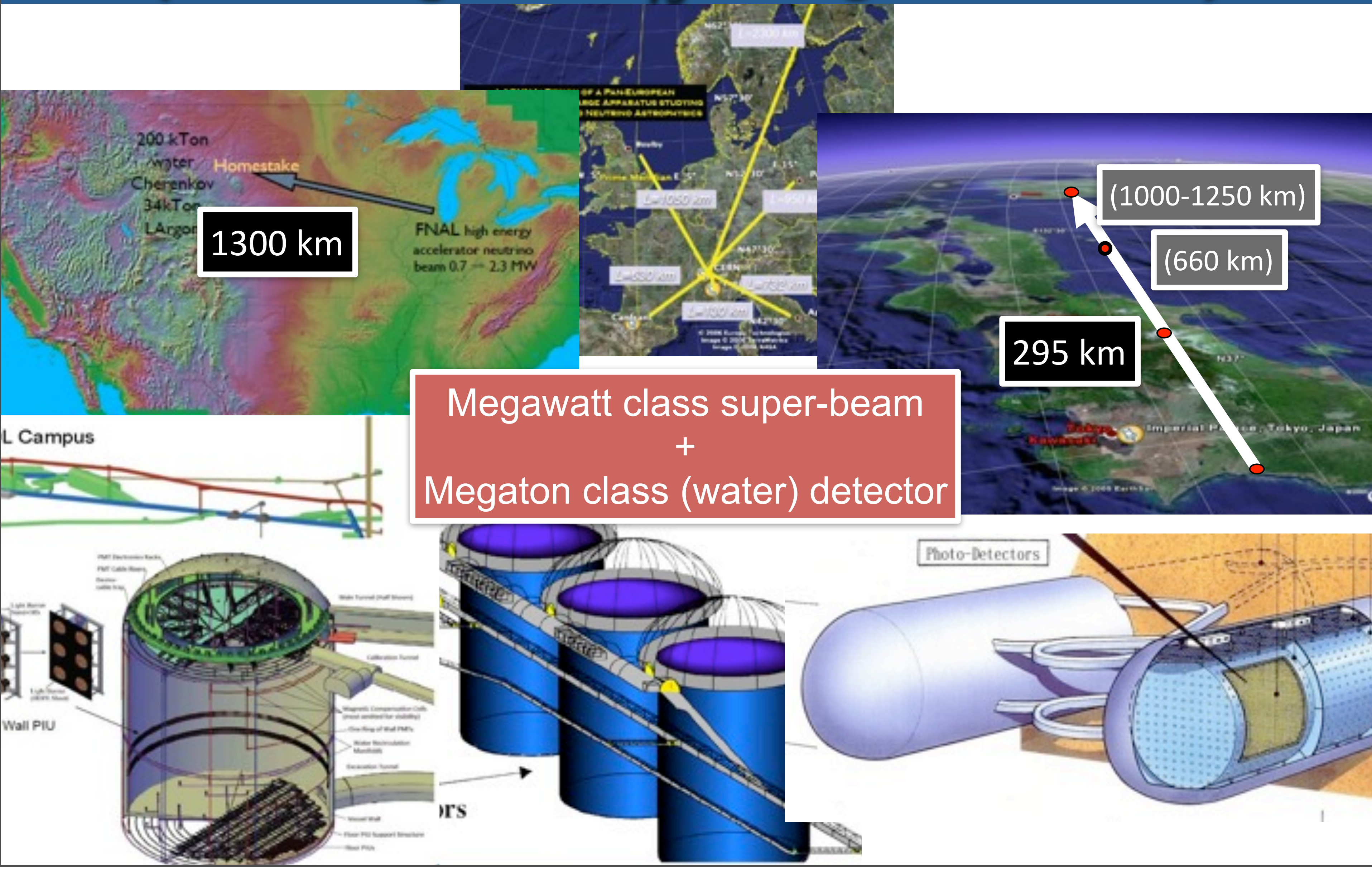
(13.7 B years)
Time

# Future LBL possibilities
## (assuming $\sin^2 2\theta_{13}$ is larger than 0.01)




Megawatt class super-beam
+
Megaton class (water) detector

# Summary

- Neutrinos have been playing major roles in the development of particle physics.
- Small but non-zero neutrino masses were discovered by studies of neutrinos produced in the Earth's atmosphere and in the Sun.
- The discovery of non-zero neutrino masses opened a window to study physics at a very high energy scale, probably Grand Unification.
- Further studies of neutrinos might tell us the origin of the matter in the Universe.

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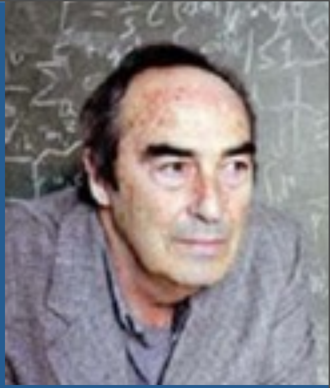
- Further studies of neutrinos might tell us the origin of the matter in the Universe.

***It is likely that future neutrino experimens will continue to be as exciting as those in the past!***

# backups

Paco Yndurain Colloquium
May 4, 2011



# *Studying massive neutrinos*

Takaaki Kajita

ICRR and IPMU, Univ. of Tokyo

# Discovery of cosmic rays

◆In the early 20$^{th}$ century, it was known that there existed natural radiation on the surface. It was assumed that they came from the earth.

◆Victor Hess carried out a balloon experiment In order to test this assumption. (The radiation should decrease in high altitudes.)

◆He observed that the radiation gets stronger in higher altitudes (of about 5km).

➔Discovery of cosmic rays
(Nobel prize 1936)

Subsequent studies found that the majority of the cosmic rays are high energy protons, He, and heavier nuclei.

# *Development of the cosmic ray studies*

- Subsequent studies found that the majority of the cosmic rays are high energy protons, He, and heavier nuclei.

- We knew that there are some cosmic accelerators that accelerate cosmic ray particles up to $10^{20}$ eV in the extreme case. (This is a very interesting scientific field. However, due to the limited time, I skip any details of the current cosmic ray studies.)

# Observation of atmospheric neutrinos

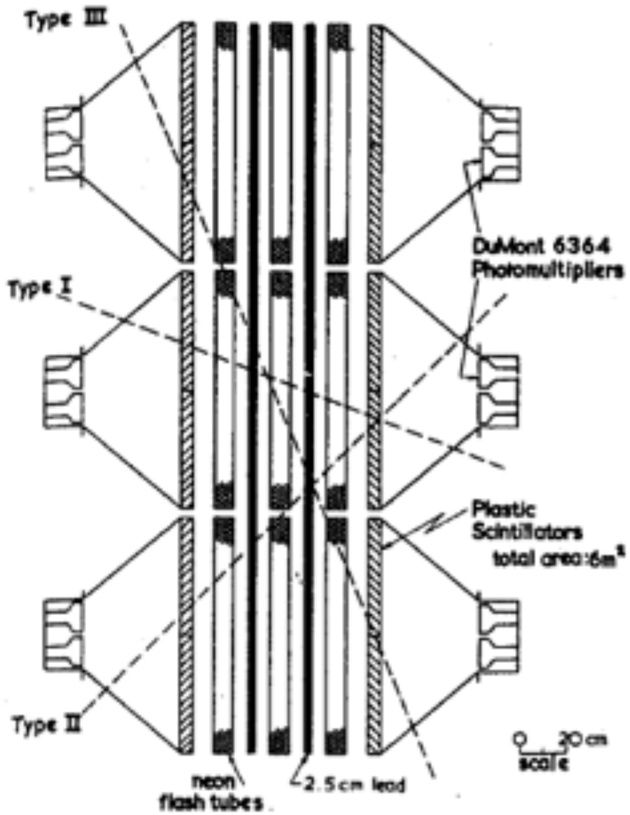
At the depth of 3200 meters (8800 meters water equivalent) in South Africa
First observed on Feb. 23, 1965
By F.Reines et al.

At the depth of 2400 meters (7500 meters water equivalent) in India (Kolar Gold Field)
First published on Aug. 15, 1965
By C.V. Achar et al.

photo of the South Africa experiment

$(\nu_\mu N \rightarrow \mu X)$

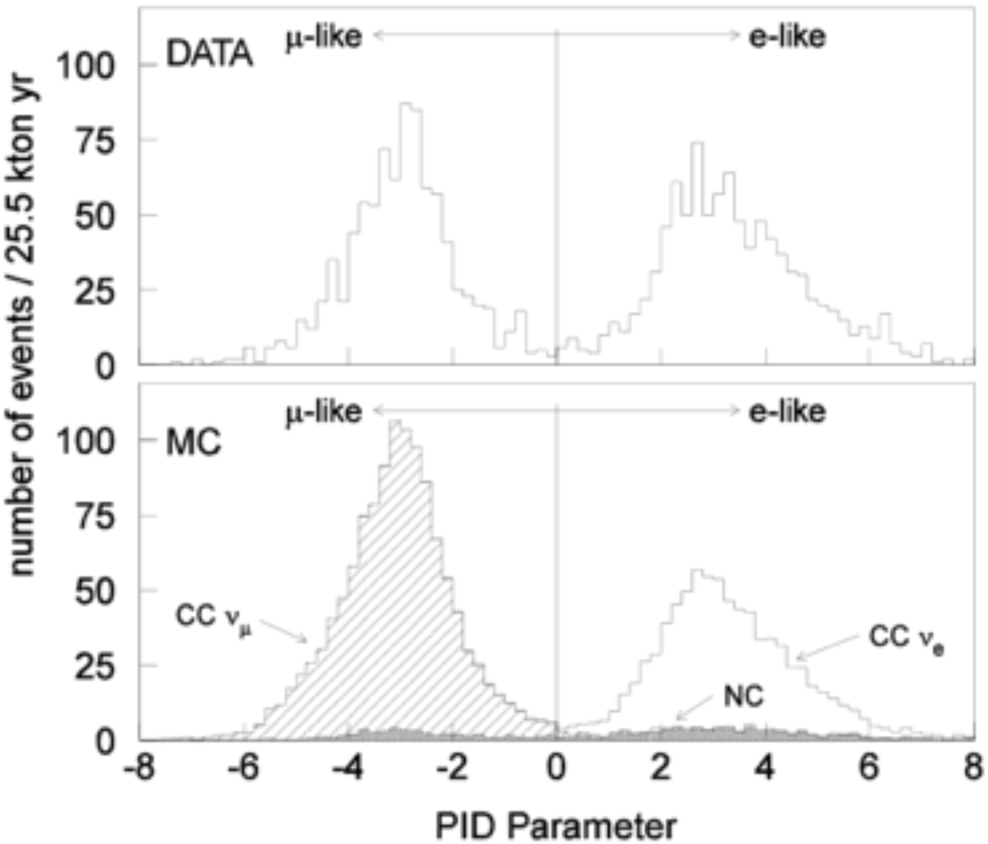
Detector for the KGF experiment



# Identifying electrons and muons

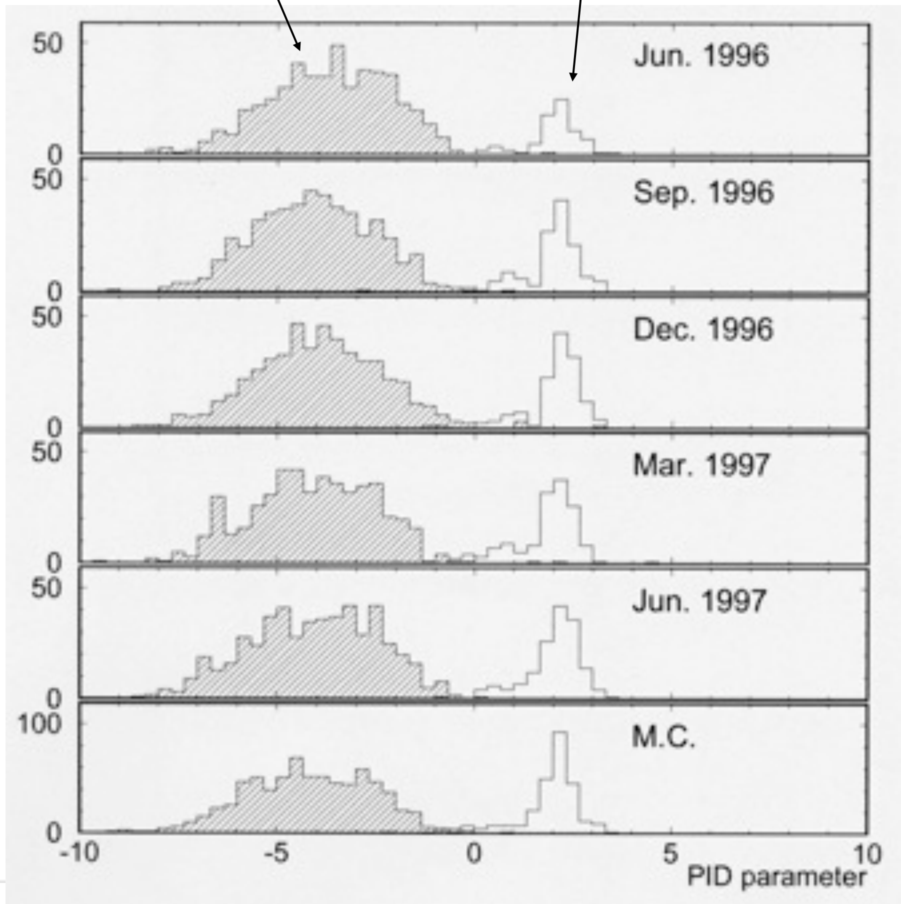
(figures from Super-K)

Atmospheric neutrino data & Monte Carlo simulation




Cosmic ray μ

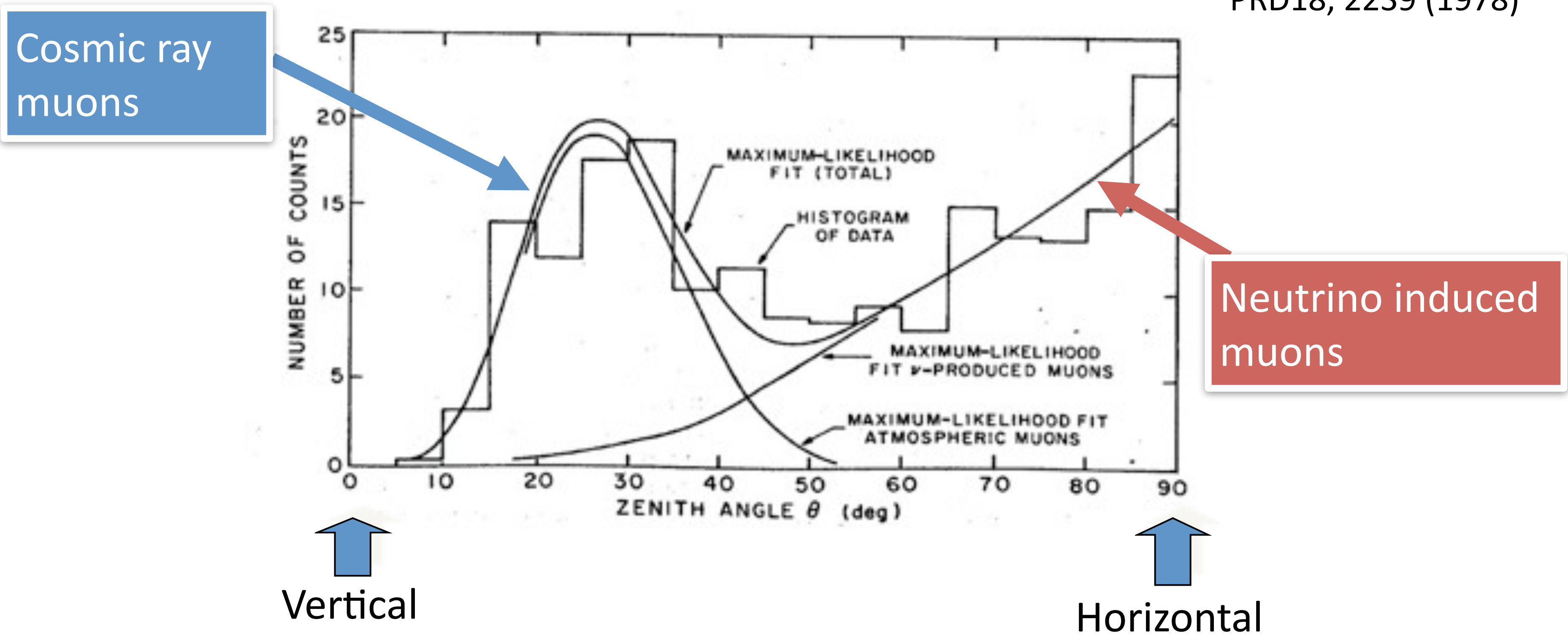
e from μ decay




ε=99%@Super-K (98% @Kamiokande)

# The first hint for the problem ?
## (South Africa experiment, 1978)

PRD18, 2239 (1978)




$$\left(\frac{Monte\ Carlo}{Data}\right) = 1.6 \pm 0.4$$

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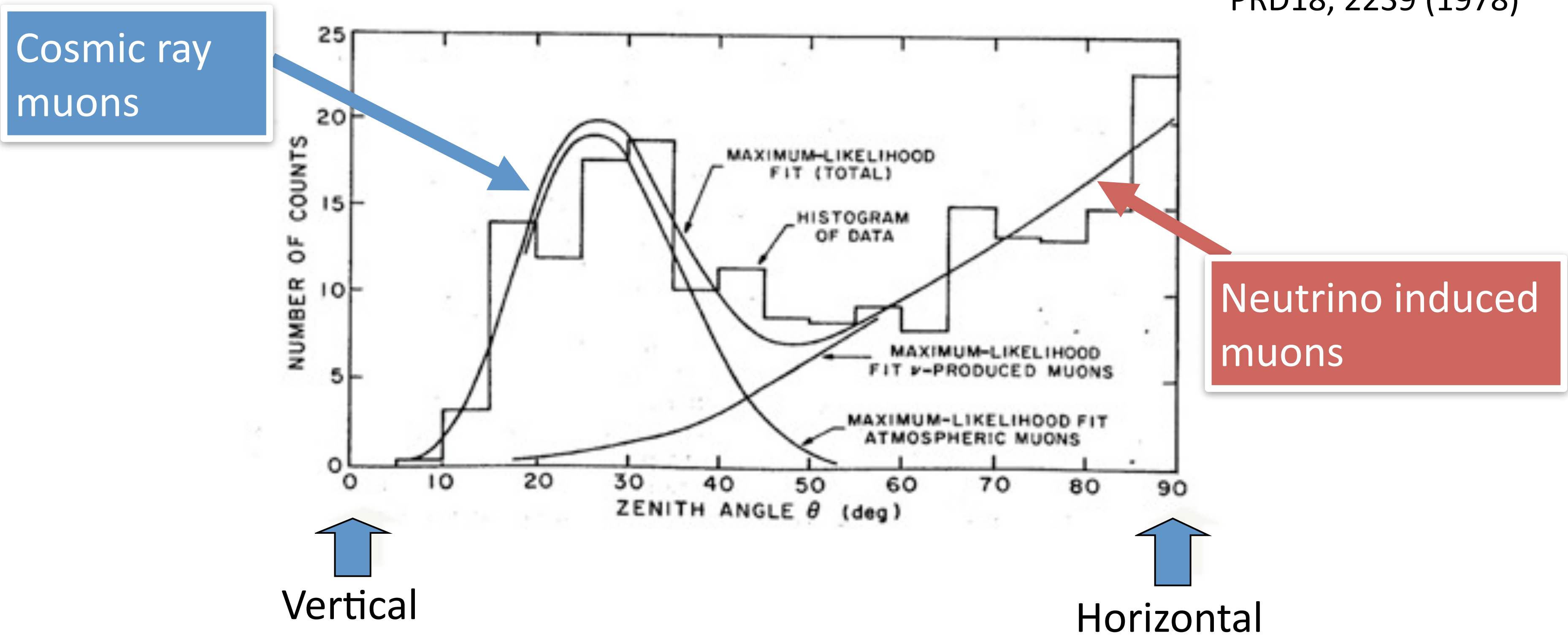



$$\left(\frac{Monte\ Carlo}{Data}\right) = 1.6 \pm 0.4$$

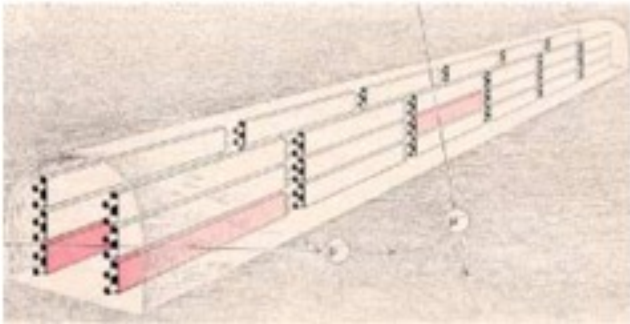
Deficit of muons

“We conclude that there is fair agreement between the total observed and expected neutrino induced muon flux …”

# Zenith angle distribution

# (updated data from the original South Africa experiment)

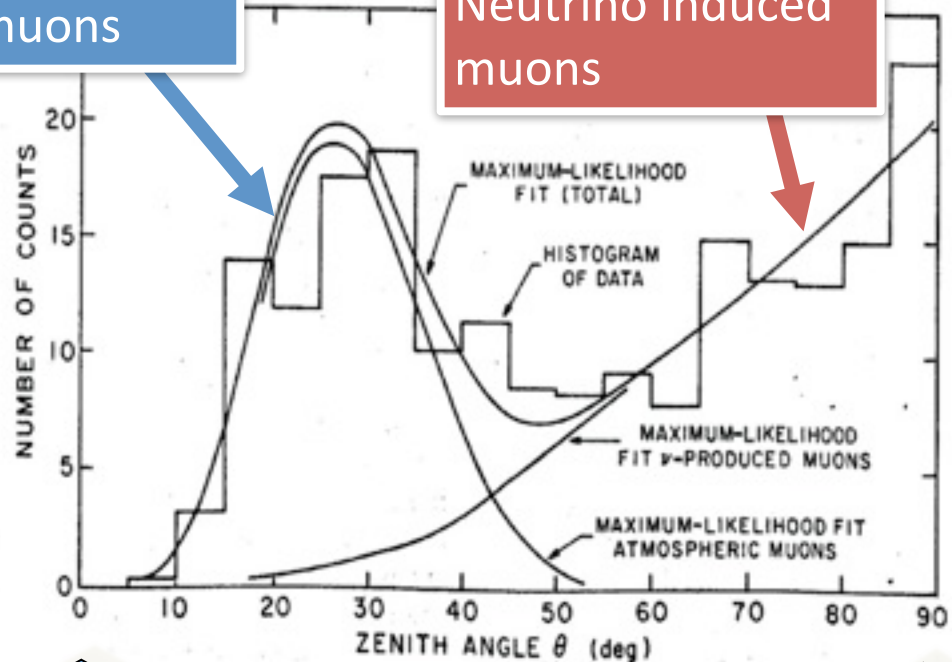
PRD18, 2239 (1978)



$(\nu_\mu N \rightarrow \mu X)$

Cosmic ray muons

Neutrino induced muons

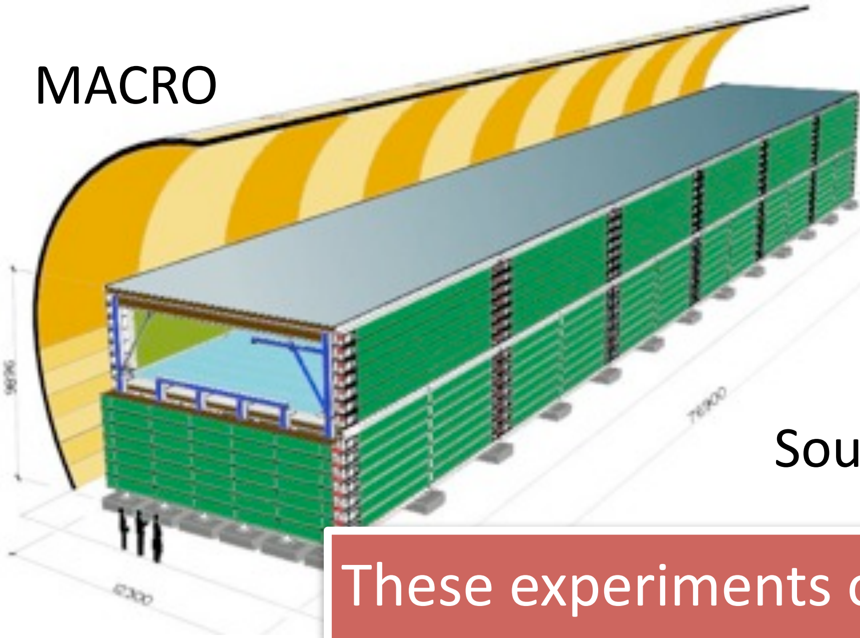



Vertical (going up or down)

Horizontal going

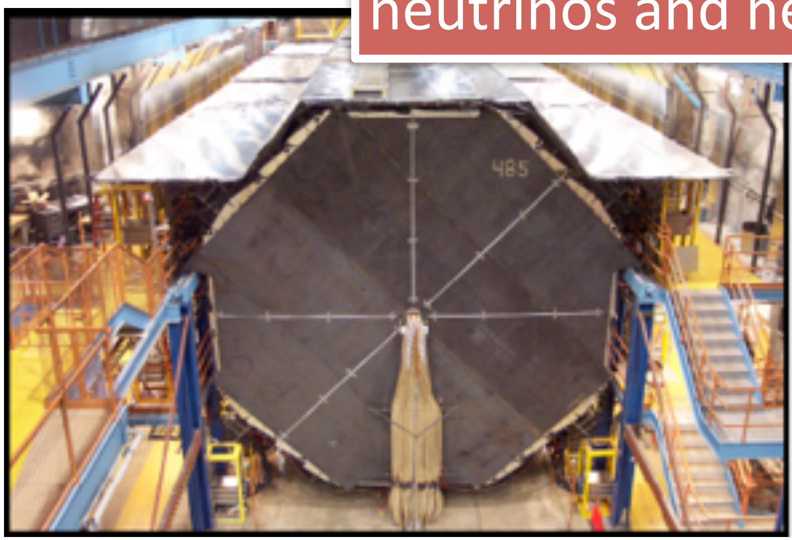
# Results from the other atmospheric neutrino

MACRO

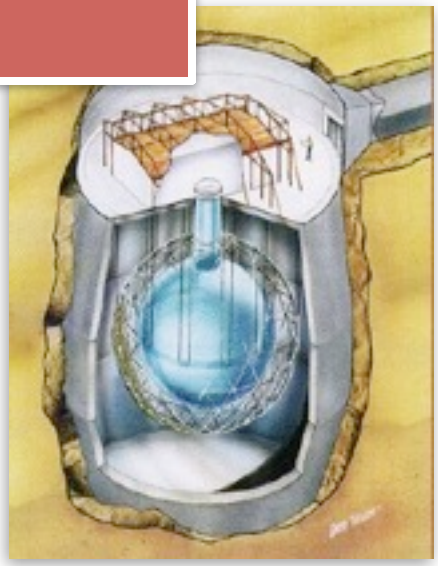


Soudan-2

These experiments observed atmospheric neutrinos and neutrino oscillations

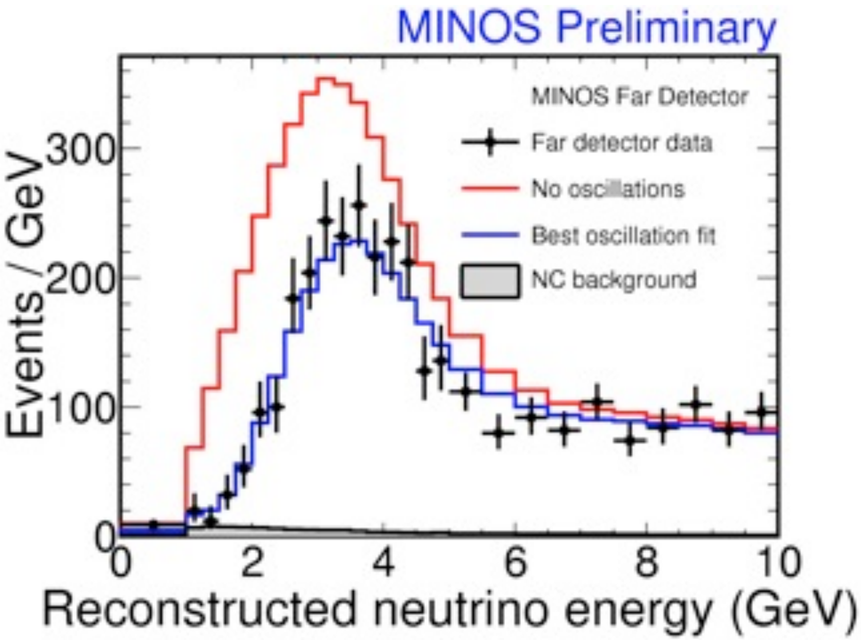


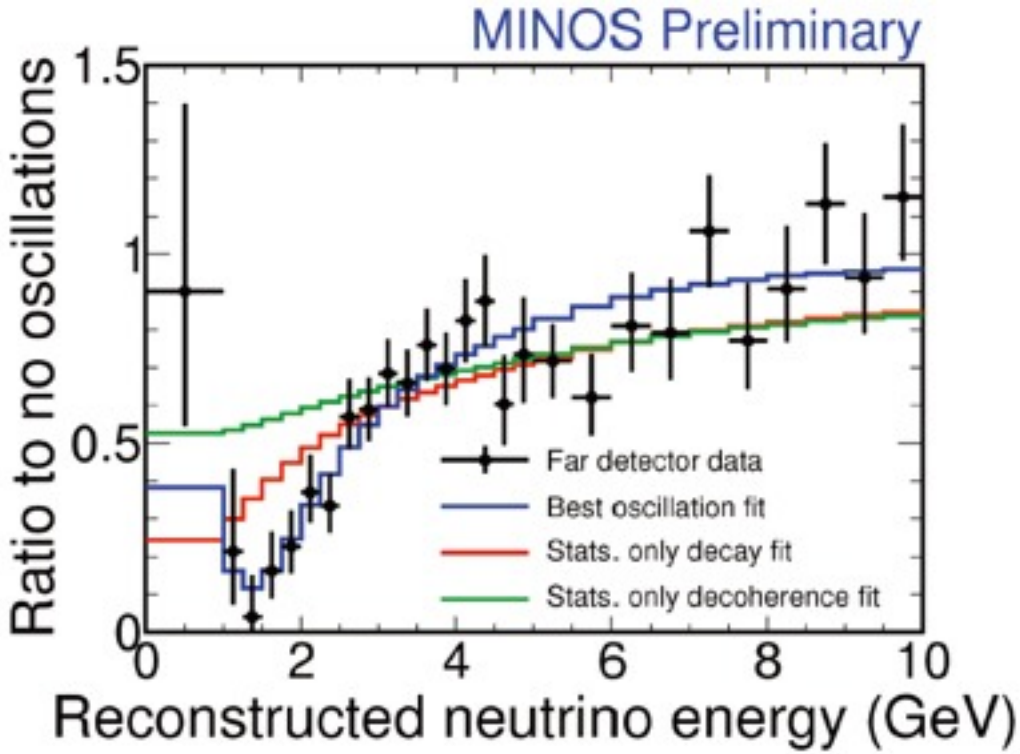
←MINOS / SNO→
(Atmospheric neutrinos only in this page)



# *MINOS* $\nu_\mu \rightarrow \nu_\tau$ *result*

$7.2 \times 10^{20}$ POT (about factor 2 improved statistics compared with the 2008 results)

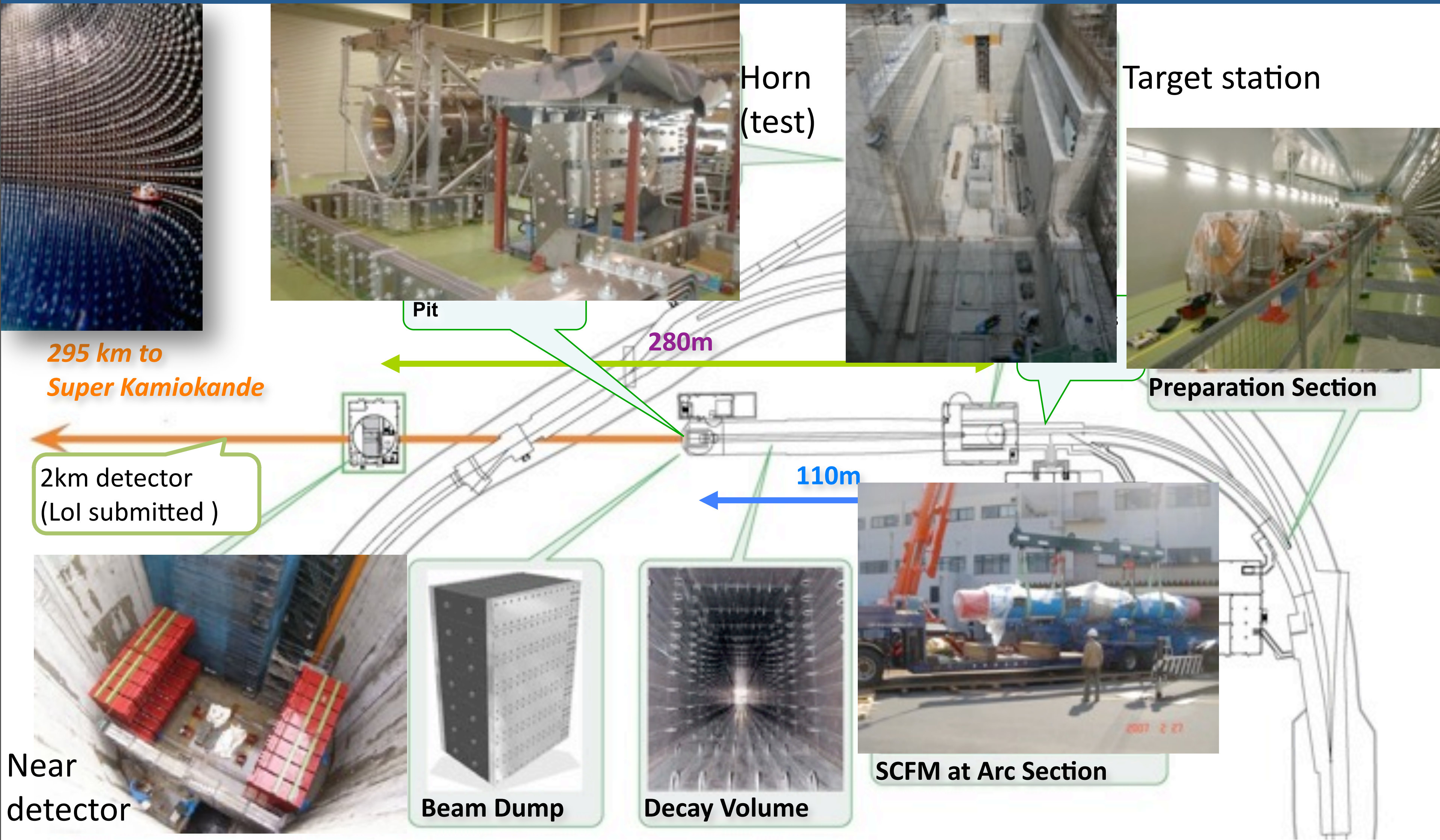



No oscillation: 2451
Observation: 1986

Oscillation gives very good fit
(Decay model disfavored > $6\sigma$)
(Decoherence model disfavored > $8\sigma$)

# T2K setup (@J-PARC)

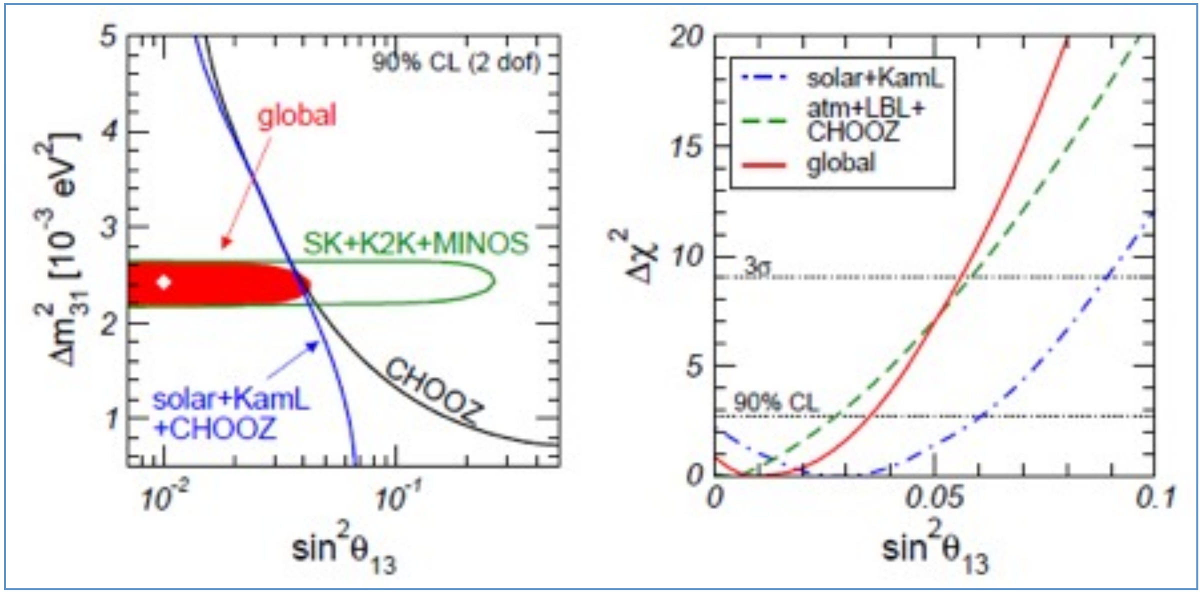


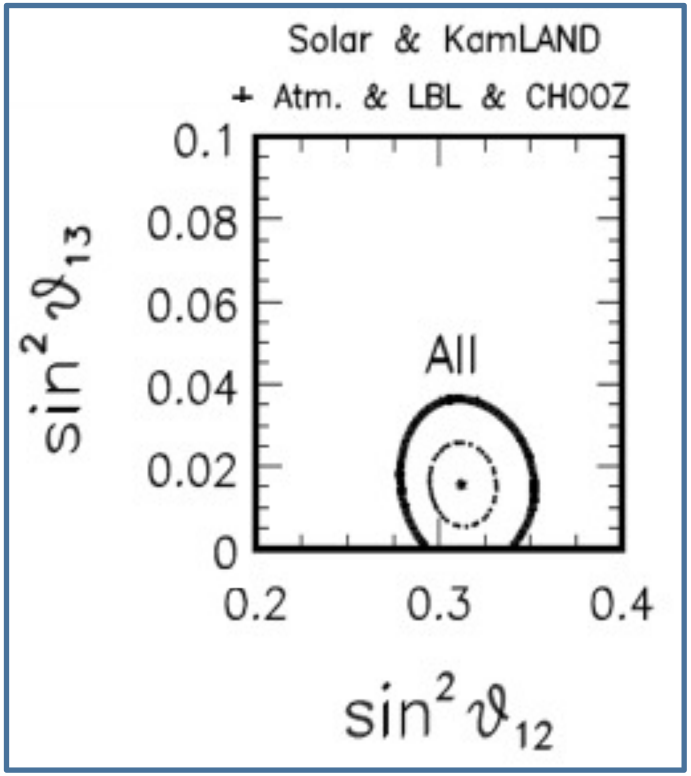

T2K experiment started in 2009 (physics run in 2010).

# 2008 $\theta_{13}$ *global fit*

arXiv:0808.2016

arXiv:0806.2649



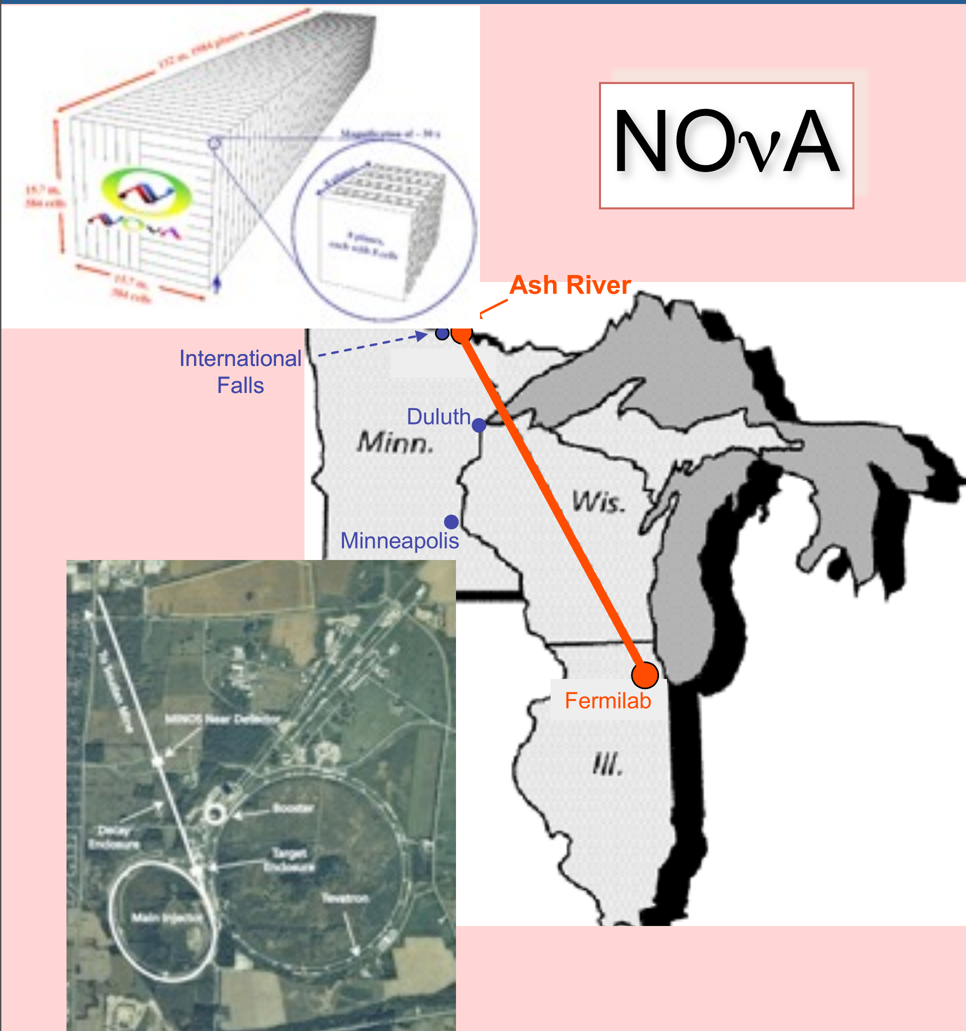

- ◆SNO and KamLAND slight tension.
- ◆CHOOZ: dominant contribution.

➔Still not clear....

Much higher sensitivity experiments required.

# LBL $\theta_{13}$ experiments

## NOνA




Will start in ～2013

## T2K

J-PARC


Super-Kamiokande

Started in 2009 (2010)

- Similar sensitivity